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TORSIONAL ELASTIC PROPERTIES OF 18 : 8 CHROMIUM-NICKEL STEEL AS AFFECTED BY PLASTIC DEFORMATION AND BY HEAT TREATMENT

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SUMMARY

A study was made of the relationship between torsional stress, strain, and permanent set for 18:8 chromium-nickel steel in the annealed, half-hard, and hard conditions. The influence of plastic extension, plastic torsion, and annealing temperature upon the torsional elastic properties is discussed. A comparison is made of these results with those obtained in the study of the tensile elastic properties.

A torsion meter of high sensitivity, especially designed and constructed for the present investigation, is described. Tubular specimens having the optimum ratio of wall thickness to diameter were tested. The relationships between mean stress and torque and between mean strain and angle of twist are given by equations derived with certain simple basic assumptions.

The influence of either prior extension or prior torsion upon the shear proof stress and the shear modulus of elasticity at zero stress is found to be quite similar to the influence of prior extension on the tensile proof stress and the tensile modulus of elasticity at zero stress. The influence of prior torsion on the linear stress coefficient of the shear modulus is somewhat similar to the influence of prior extension on the linear stress coefficient of the tensile modulus. The influence of prior deformation on the corresponding quadratic stress coefficients of the respective moduli, however, is dissimilar.

The torsional and tensile elastic properties are influenced in a similar manner by change in annealing temperature.

The factors involved in the variation of the torsional elastic properties with prior extension, prior torsion, and annealing temperature are shown to be (a) internal stress,

which may be either macroscopic or microstructural; (b) work-hardening or lattice expansion, and (c) crystal reorientation.

INTRODUCTION

During the past seven years, the National Bureau of Standards has been studying properties of high-strength aircraft metals, a project sponsored by the National Advisory Committee for Aeronautics. The previous reports of this investigation (references 1, 2, and 3) discussed the tensile elastic properties of metals with particular reference to their elastic strength and modulus of elasticity. A paper by the same authors (reference 4) describes the results of an investigation, not sponsored by the NACA, of the tensile elastic properties of some metals not included in the NACA reports.

Because the boundary between elastic and inelastic strain is indefinite, it was found necessary to evaluate the elastic strength in terms of a number of indices, termed "proof stresses." These are the stresses necessary to cause permanent extensions of 0.001, 0.003, 0.01, 0.03, and 0.1 percent. The tensile stress-strain line for many metals is curved; hence the tensile modulus of elasticity cannot be expressed by a single numerical value but only in terms of several indices. The indices used in the previous reports are the modulus of elasticity at zero stress E_0 and the linear and the quadratic stress coefficients of the modulus C_0 and C'. When these various indices are known, the tensile elastic properties of metals are fairly well defined. In earlier investigations studies were made of the effect of plastic deformation and heat treatment upon the tensile elastic properties at both room temperature (references 1 and 2) and sub-zero temperature (reference 3).

In many structures and machines, forces that set up large shearing stresses in drive shafts and other connecting members are transmitted as torques. A knowledge of the reaction of metals to pure shearing forces therefore is desirable. The phase of the investigation now in progress deals with the shear elastic properties of different high-strength aircraft metals based on tests of thin tubular specimens subjected to torsional loading producing shear.

The present report discusses the results of torsion tests of steels of the 18-percent chromium and 8-percent nickel type widely used to fabricate high-strength members for aircraft structures. The properties considered are shear proof stress, shear modulus of elasticity and its stress coefficients, and the variation of these indices with plastic extension, plastic torsion, and heat treatment. The fundamental factors underlying the results also are discussed. Throughout this paper, the terms "torsion" and "shear" will be used synonymously.

MATERIALS AND APPARATUS

Materials and Specimens

The 18:8 chromium-nickel steel tubing was supplied in three grades of hardness - annealed, half-hard, and hard. The compositions of these metals are given in table I. The thermal and cold-working treatments applied in the laboratory on some of these specimens are indicated in table II. The initial torsional properties are found in table III.

All the metal tubes were of 1-inch outside diameter and 0.1-inch wall thickness, nominal size. Specimens were cut from these tubes into lengths of about 15 inches and the ends were squared in a lathe. The specimens then were cleaned thoroughly, after which the length, the diameter, and the weight of each was accurately determined. From these data and from density values measured on small samples of the same material, the average wall thickness of each specimen was computed.

Apparatus

The machine used for the torsion tests was of the manually operated pendulum type having a capacity of 13,000 inch-pounds. The mounting of the specimen and torsion meter for measuring strain is shown in figure 1. The ends of the tubes were reinforced by two steel plugs of proper diameter and the tubes then were clamped firmly between wedge-shape jaws.

A torsion meter of high sensitivity, especially designed and constructed for measuring strain in this investigation, is shown in detail in figure 2. It consists of two similar rings A and A' (ring A' is not visible) spaced $2\frac{1}{2}$ inches on centers, each fastened to specimen S by three setscrews B and B'. To ring A' is rigidly attached a hollow metal cylinder C, which extends over ring A; there is a slight clearance between cylinder C and ring A. To cylinder C are attached two ordinary glass prisms D and D' and to ring A two glass roof prisms E and E'; one set of adjacent ordinary and roof prisms D and E is diametrically opposite to set D' and E' with respect to specimen S. After proper adjustment of the position of each set of prisms, the relative angular motion of rings A and A' was measured by Tuckerman optical collimator (reference 5). The readings from both sets of prisms were averaged to eliminate the angular displacement due to any slight bending of the tubular specimen that may accompany appreciable plastic straining.

In order that the gage length over which angular twist was to be measured could be set accurately, cylinder C was held rigidly to ring A by three screws (not shown) at position F while the torsion meter was being attached to the tubular specimen. These screws were removed before the test. Although readings could be taken only over a shear-strain range of less than 1 percent during a single setting of the torsion meter, it was possible by resetting the meter, with the aid of the three placement screws at F, to extend indefinitely the range over which strains could be measured.

The smallest division on the collimator scale represents a relative angular motion of the two rings of 0.0002 radian, which corresponds to a change in strain of less than 0.004 percent. By means of a vernier on the collimator scale, changes in strain could be measured directly to less than 0.0002 percent.

MEASUREMENT OF STRESS, STRAIN, AND PERMANENT SET IN TORSION

Method of Test

In order to investigate the relationship between stress, strain, and permanent set for a metal undergoing shear, a torsional stress-set curve and a correlated torsion stress-strain curve were determined. For this purpose the specimen was loaded and unloaded cyclically in torsion to progressively greater values of torque until a plastic shear strain or torsion set of about 0.1 percent had been reached. The minimum value of torque (unloaded state) in each cycle was 180 inch-pounds. By plotting the maximum shear stress for each cycle against the corresponding total shear strain, a torsional stress-strain curve was obtained. By plotting the maximum shear stress for each cycle against the corresponding value of total plastic shear obtained after reducing the torque to 180 inch-pounds, a torsional stress-set curve was obtained. This procedure is analogous to that used in the investigation of the tensile elastic properties of metals (references 1 to 4).

In obtaining such correlated curves, it was important to adhere to a carefully predetermined time schedule. For a series of cycles, the rates of loading and unloading were about the same for each cycle. The maximum and minimum loads for all cycles were each maintained for a period of 2 minutes. Torsion-meter readings were obtained at the beginning of the series of cycles and at the end of each 2-minute holding period.

The total torsional set or total plastic shear at the end of any cycle (180-in.-lb load) was computed from the difference between the meter reading at the end of such cycle and the reading at the beginning of the series of loading cycles. The torsional set or plastic shear obtained during a single cycle is equivalent to the difference between the positive and the negative torsional creep occurring during the cycle. Positive creep will occur while approaching and maintaining the upper load; negative creep will occur while approaching and maintaining the lower load. The total strain for any load was computed from the difference between the torsion-meter reading at that load and the reading at the beginning of the series of cycles.

In order to investigate the influence of prior plastic torsion on the torsional stress-set and stress-deviation curves, after the determination of the initial curves, some specimens were twisted plastically by numerous successive increments of plastic shear until definite signs of buckling of the tube were noted. Correlated torsional stress-strain and stress-set curves were obtained after each increment of plastic shear. Some of these increments were equivalent only to the plastic shear obtained in the tests upon which the previous stress-set curve was based; others were much larger. Between these increments of plastic shear, the specimen was allowed to rest after unloading before determining the subsequent stress-set and stress-strain curves.

The duration of such a "rest interval" has a pronounced influence upon the form of the stress-set and stress-deviation curves derived from subsequent measurements.

Certain changes will occur in the test specimen during the rest interval, as evidenced by negative shear creep during this period. This creep is analogous to the negative creep in tension occurring during rest between successive tensile loadings of a specimen.

The prior plastic torsion for any one series of cycles will be defined as the difference in shear strain , as obtained at the 180-inch-pound load, at the beginning of that series and at the beginning of the first series. Since the torsion meter was reset after each series of cycles, the prior plastic torsion actually was measured as the sum of the total torsion sets given the specimen prior to that series. The terms "prior plastic torsion," "plastic torsion," and "prior torsion" are used synonymously in this report.

Calculation of Stress and Strain Values

and Presentation of Results

Since the tubing selected for test was of appreciable thickness in order to permit large amounts of plastic shear without buckling, the shear stress and therefore the shear strain increased somewhat from the inner to the outer portions of the wall.

An exact determination of the shear stress at any radius is possible (reference 6), but complicated, since the distribution of stress along a radius is dependent upon the form of the shear stress-strain curve of the metal. The shear strain or torsion set γ at radius r is given by the relation

$$\gamma = \frac{r\theta}{l} \tag{1}$$

where θ is the angle of twist produced in gage length l.

Methods of approximation, based on some simplifying assumptions, generally are used to determine the shear stress and strain. In this report, the method chosen (reference 6) was based on the calculation of the stress and strain in the mean fiber on the assumption that both stresses and strains increase linearly with the distance from the axis of the tube, as they do in the elastic case. The following notation is used:

M applied torque, inch-pounds

D outer diameter of tube

t thickness of tube

$\bar{r}$ mean radius $= \frac{D-t}{2}$

the shear stress

$$\tau = \frac{2}{\pi}\frac{M}{D^2 t}\left[\frac{1}{1 - 2\frac{t}{D} + 2\left(\frac{t}{D}\right)^2}\right] \tag{2}$$

and the shear strain

$$\gamma = \frac{\bar{r}\theta}{l} = \frac{\theta D}{2l}\left(1 - \frac{t}{D}\right) \tag{3}$$

It can be shown that for $t/D = 0.12$ the stresses so calculated would not differ by more than 14 percent from any stress existing in the wall and that the stresses at the mean fiber calculated from equation (3) could not be in error by more than 1.5 percent. Since torsional deformation of a tubular specimen produces only negligible changes in the dimensions of the tube, values of stress, strain, and set were based upon original dimensions.

By the use of tubes having nominally constant values of t and D, a comparison of values of stress and strain obtained with different specimens would be valid, nothwithstanding the form of equation (2) or (3). Shear stress-set curves were derived from values of shear stress and torsion set calculated by equations (2) and (3).

The shear stress-strain relationship is best studied by use of the shear stress-deviation curve. Such a curve is obtained by plotting against the shear stress, not the total shear strain, but the difference between the total shear strain produced at the maximum load for each cycle and a strain for a corresponding load computed on the basis of an assumed constant value of the shear modulus of elasticity. These differences represent deviations of the actual stress-strain curve from a straight stress-strain line the slope of which is based on the chosen value of the modulus. With a suitable choice of the assumed value of the modulus; the stress-deviation curve gives a very sensitive representation of the variation of strain with stress.

Accuracy of Set and Strain Values

As previously noted, values of strain and set are determined from readings made at each upper and lower load. During the making of strain measurements, any deviation from the selected load setting will introduce an error in the test because of a resultant change in elastic strain. This deviation will depend upon the accuracy of reading the dial, the ability of the testing-machine operator to adjust and maintain the load during measurement, and the frictional torque of the bearings between the pendulum and the specimen. Because of the high gear ratio in the loading mechanism and the use of ball bearings between the pendulum and the specimen, errors due to the two factors last mentioned are negligible. By use of a vernier on the loading scale, shear-stress variations of about 70 pounds per square inch could be detected. If a shear modulus of 11,000,000 pounds per square inch is assumed, this value corresponds to a shear-strain error of about 0.0006 percent. Such an error will be minimized when a number of experimental points are used in fairing the stress-set and the stress-deviation curves. The actual errors do not appear sufficient to invalidate the conclusions drawn from the tests.

INFLUENCE OF PLASTIC EXTENSION ON TORSIONAL ELASTIC PROPERTIES OF ANNEALED 18:8 CHROMIUM-NICKEL STEEL

The torsional elastic properties of 18:8 chromium-nickel steel, determined for the material in the as-received conditions, designated annealed TA, half-hard TB, and hard TC are listed in table III. The determination of these values is discussed later.

In order to obtain this alloy in intermediate stages of cold work, a series of hard-grade specimens were treated as follows: They were initially softened by heating to 1900° F and water quenching; the heating at 1900° F completely dissolved all carbides and the subsequent quenching prevented their reprecipitation at the grain boundaries. The material so treated was less hard than the annealed material as received. By using the initially hard-grade material, structural uniformity was assured. Some of the specimens thus treated were then extended different amounts in a tension-testing machine; these extensions were 0.5, 1.0, 2.0, 3.0, 5.0, 10.0, and 20.0 percent. The steel reinforcing plugs later required in the torsion tests were inserted in the ends of these specimens prior to these extensions. Careful measurements were made of the extension and of the average diameter of the reduced section of each tube. The tests of this series of specimens and of an unextended annealed specimen will next be considered.

Torsional Elastic Strength as Influenced by Prior Plastic Extension

Shear stress-set curves and correlated stress-deviation curves, derived from torsion tests made upon the specimens previously extended various amounts, are shown in the upper and lower rows, respectively, of figure 3. Only single curves were obtained for each specimen. The percentage of prior tensile extension given each specimen after annealing is indicated on the corresponding curve. In the lower portion of the figure, abscissas represent values of torsional set as derived by equation (3); the scale of abscissas is indicated and expressed as percent torsion (strain). The ordinates represent shear stress, which is computed by using equation (2) and is based on the dimensions of each specimen after prior extension.

The stress-set curves show that the highest values of shear stress over the indicated ranges of permanent set were obtained for the specimens having the largest prior extensions. The slopes of these curves over the lower stress range, however, vary in a different manner; the steepness of these curves decreases progressively for the initial stages of prior extension and then increases during subsequent stages. The shear proof stresses corresponding to selected values of plastic shear or torsion set, termed "proof sets," were determined from stress-set curves. The values of proof set selected were 0.001, 0.003, 0.01, 0.03, and 0.1 percent; these values are numerically the same as those used in the determination of the tensile proof stresses of metals.

The variation of shear proof stresses with prior extension for these specimens is shown in figure 5. The proof-stress curves for 0.01-, 0.03-, and 0.1-percent set rise continuously with increasing values of prior extension. The curve for 0.001-percent proof set, however, decreases to a minimum for small values of extension and rises only slightly with further extension; it is thus qualitatively similar to the corresponding curve for tensile proof stress (references 1 and 2).

In reference 4 it was noted that the oscillations in the tensile proof stress-extension curves might be attributed to variations of one or more kinds of internal stress. As shown by Heyn and Bauer (reference 7) and by Masing (reference 8), the internal stresses induced by plastic deformations are of three kinds. The first kind, which is referred to in this report and in reference 4 as macroscopic internal stress, is caused by nonuniformity of plastic deformation in different parts of a cross section. Such internal stress tends to lower the observed elastic strength. The second kind, referred to as microstructural stress, is caused by initial differences in the resistance to plastic deformation of variously oriented grains or to differences in the strength of different microconstituents; this type occurs when the metal is stressed beyond its yield strength. Masing has attributed the cause of the Bauschinger effect and of negative creep to the second type of internal stress; that is, it tends to increase the resistance to deformation of the metal in the direction of previous loading and to decrease the resistance in the opposite direction. There is some evidence, however, that the influence of microstructural stress is very similar to the influence of macroscopic internal stress.

The third kind of internal stress described by Heyn and Masing is associated with space-lattice changes involved in work hardening. It has been shown by Smith and Wood (reference 9) that plastic extension of iron causes the existence of a three-dimensional expansion after removal of the stress. This type of internal stress cannot be totally eliminated except by recrystallization. There is some evidence that the lattice expansion increases linearly with increasing plastic deformation. The lattice expansion is associated with one or more structural changes (other than change of crystal orientation) occurring during work hardening, such as slip on crystal planes, grain fragmentation, and so forth. There is some evidence that the Bauschinger effect is partly or wholly due to lattice expansion. In the present report, as in earlier reports, the term internal stress does not apply to stresses due to space-lattice changes. The influence of space-lattice changes – that is, the lattice-expansion factor (the term work-hardening factor also has been used in previous papers) – will be referred to frequently in this report.

The increase in macroscopic or microstructural internal stress, after slight plastic deformation, probably predominates in causing the initial lowering of the 0.001-percent shear proof stress as shown in figure 5. At greater values of prior extension, however, the subsequent rise of the 0.001-percent proof stress probably is due to the predominant influence of the lattice-expansion factor. The progressive rise of the proof-stress curves for 0.01-, 0.03-, and 0.1-percent set is a manifestation of the predominance of the lattice-expansion factor through the entire range of prior extension. As separate specimens were used at each value of extension, the influence of varying rest intervals and extension spacing was not a controlling factor. Therefore, significant fluctuations in the proof-stress curves do not occur.

In reference 2, the work-hardening index of a metal was empirically defined as the ratio of the 0.1-percent tensile proof stress measured after 3-percent extension to that obtained before extension. This ratio for the annealed alloy was found to be 1.74. The ratio determined in a similar manner for the 0.1-percent shear proof stress is 1.70. Computations based on work by Nadai (reference 10) would indicate that a 0.1-percent tensile strain causes shear strain in the direction of the maximum shear stress about equivalent to that caused by a 0.15-percent torsion strain (reference 6). Although values of plastic torsion as great as 0.15 percent were not obtained during any single setting of the torsion meter, the nearly horizontal slopes of the stress-set curves above 0.10-percent torsion (fig. 3) would indicate that the ratio for the 0.15-percent torsion proof stress would not differ greatly from the value of 1.70. This fact suggests that tensile and torsion stress-set measurements give similar values for the work-hardening index.

As shown in table III, the values of shear proof stress for the half-hard and the hard alloy are significantly greater than those obtained for the metal extended 20 percent. As previously noted, the values of shear proof stress for the material annealed in the laboratory were lower than those for the material as received. It is not known whether this difference is attributable to a difference in annealing temperature used in the two cases or to a possible finishing treatment given the as-received annealed material in straightening rolls or dies that would impart cold work.

Effect of Plastic Extension on Shear Stress-Deviation Curve

An incomplete view of the elastic properties of a metal is obtained by considering only the relation between stress and the residual deformation after the applied stress is released. The influence of stress on the accompanying total strain and on the elastic strain should also be considered. These relationships are revealed by the stress-deviation curves and by subsequently derived curves and indices.

In the upper portion of figure 3, the broken-line curves represent deviation values calculated from stress and strain measurements by the method described in the preceding section, using an assumed value of 11×10^6 pounds per square inch for the shear modulus. The solid-line (corrected) curves were derived from the broken-line curves by deducting values of set obtained from corresponding shear stess-set curves immediately below. Abscissas represent values of deviation; the scale of abscissas is indicated and expressed in percent torsion (strain). The corrected shear stress-deviation lines are generally curved, indicating a decrease of the modulus of elasticity with increase in stress. With an increase in the value of prior extension, the general slope of the corrected curve decreases, thus indicating a corresponding decrease of the mean value of the modulus. The relationship between the curves is better revealed by the derived diagrams (figs. 4 and 6).

Variation of Shear Modulus with Stress as Influenced by Plastic Extension

The shear secant modulus, given by the ratio of stress to elastic strain, is used in this report to study the variation of the shear modulus of elasticity with different stresses. The tensile secant* modulus was used in the previous reports to study the influence of several factors on the variation of Young's modulus with stress.

The variation of the shear secant modulus of elasticity with stress derived from the corrected stress-deviation curves in figure 3 are shown in figure 4. The prior extension in percent, given each specimen, is indicated on the corresponding curve.

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*This modulus differs from a frequently used secant modulus based on the variation of total strain with stress.

The points indicated in figure 4 do not correspond to stresses at which strains were measured, but to selected points on the corrected shear stress-deviation curves for which the secant moduli were evaluated.

With the exception of the curve for 5-percent extension, the lines are vertical over the lower part of the stress range. The curve for 5-percent extension shows a continuous decrease in modulus with increase in stress. The curvature of the shear stress-modulus lines at the higher stress values indicates a slight decrease of the modulus values.

The shear modulus at zero stress G_0 may be determined directly from the shear stress-modulus line by extrapolating to zero stress (references 2 and 4). When the modulus line is straight, the variation of the secant modulus of shear G with shear stress S may be represented by

$$G = G_0 - kS \tag{4}$$

The constant k is the cotangent of the angle of slope of the shear stress-modulus line. It has been found more convenient to express equation (4) in the form of

$$G = G_0(1 - C_0 S) \tag{5}$$

where $C_0 = k/G_0$ represents the linear stress coefficient of the secant modulus.

When the torsional stress-modulus line is curved from the origin, the stress coefficient of the modulus C_0 according to equation (5) would no longer be constant but would vary with stress. By adding another term to equation (5), such a stress-modulus line may be more correctly represented as

$$G = G_0(1 - C_0 S - C'S^2) \tag{6}$$

where C_0 and C' are both constant. The constant C' is the quadratic stress coefficient of the modulus and is an index of the curvature of the stress-modulus line. Use of the second coefficient C' will be made in the discussion of some of the test results in this report. In figure 4, however, the values of C' would be small and therefore were not derived.

Values of C_0 are indicated (see fig. 4) by a number adjacent to each stress-modulus line. The value of G_0 for each stress-modulus line is indicated by the intersection of that line with the axis of abscissas.

It is evident that values of C_0 and C' change according to variations in the form of the corrected stress-deviation curve. The general equation for this curve as derived from equation (6) is

$$\epsilon = S/G = S/G_0(1-C_0S-C'S^2) \qquad (7)$$

where ϵ is the corrected shear strain. As the linear and quadratic terms are small compared with unity, equation (7) may be written as

$$\epsilon = \left(\frac{1}{G_0}\right)(S + C_0S^2 + C'S^3) \qquad (8)$$

Since the strain corresponding to the tangent to the stress-strain line at the origin is S/G_0, the deviation ϵ_d from this tangent is

$$\epsilon_d = \epsilon - S/G_0 = \left(\frac{1}{G_0}\right)(C_0S^2 + C'S^3) \qquad (9)$$

When the stress-modulus line is straight, C' is zero and the last term in the parentheses of equation (9) disappears. The stress-deviation relationship corresponding to a straight stress-modulus line, therefore, is represented by

$$\epsilon_d = C_0\ S^2/G_0 \qquad (10)$$

which is the equation of a quadratic parabola. When C_0 is zero and the derived stress-modulus line is curved, equation (9) becomes

$$\epsilon_d = C'S^3/G_0$$

which is the equation for a cubic parabola.

It is possible that the shear stress-deviation curves are more accurately represented by equations of a different form, involving additional polynomial terms, or by a mathematical expression of a different type. If the near linearity of the derived stress-modulus curves is considered, however, use of the empirical equations is justified.

Influence of Plastic Extension on Shear Modulus of Elasticity

Figure 6, based on the values of G_0 and C_0 derived from the curves in figure 4, shows the variation of G_0 and C_0 with prior plastic extension of the annealed alloy. Abscissas represent plastic extension in percent. The ordinate scale on the left-hand margin represents values of the shear modulus at zero stress G_0 plotted in the upper curve. The scale of values of C_0 plotted in the lower curve is found on the right-hand margin.

The shear modulus of elasticity G_0 decreases generally with increase of prior extension (fig. 6). The value of C_0 was zero in every case except for the 5-percent extension. The positive value of C_0 indicates that the corresponding stress-deviation curve in figure 3 is not linear over the lower stress range. Such deviation from linearity is not apparent in figure 3 and was measurable only when the curve was drawn to the much larger scale used for the original diagrams. No great significance should be attached, therefore, to this singular deviation in the C_0 extension curve. Prior tensile extension does influence the values of G_0 but has little influence on C_0.

Influence of Various Factors upon Torsional and Tensile Elastic Properties as Affected by Plastic Extension

In references 2 and 4 it was noted that the variation of the tensile elastic properties with extension or with annealing temperature could be directly associated with three important factors: namely, (a) internal stress, which may be either macroscopic or microstructural; (b) lattice-expansion or work-hardening factor; and (c) crystal reorientation. The first two factors were described previously in this section. The term crystal reorientation as used in this paper implies the change from a state of random orientation to a preferred state after appreciable deformation. This change may have a pronounced influence upon the elastic properties of many metals.

Increasing macroscopic or microstructural internal stress will tend to decrease the tensile proof stresses and increase the tensile modulus of elasticity and its linear and quadratic stress coefficients C_0 and C'. An increase in the lattice expansion is accompanied by an increase in the tensile proof stresses and a decrease in the tensile modulus of elasticity and its stress coefficients.

The influence of the crystal-orientation factor is revealed only by variation of the modulus of elasticity; apparently it has little influence upon C_0, C', or the other elastic properties. Its influence is dependent upon the directional variation of the modulus of elasticity with respect to the principal crystal axes and upon the preferential crystal orientation found in the metal after appreciable cold work. Detailed discussions of this subject are given in references 2 and 3.

The variation of the several elastic properties with prior extension, with prior torsion, or with annealing temperature will depend upon the relative dominance of these several factors.

The shear modulus at zero stress G_0 (fig. 6) and the tension modulus at zero stress E_0 (reference 2)* for the annealed 18 : 8 alloy, in general, decrease progressively with increasing plastic extension. This decrease is attributed in both cases to the predominant influence of the lattice-expansion factor. It has been noted that the progressive increase of the torsional proof stresses with prior extension as shown in the curves for 0.01- to 0.10-percent set of figure 5 can be attributed to the predominant influence of lattice expansion. A similar relationship has been found for tensile proof stresses.

In tension tests, in which single annealed specimens were given a series of successive extensions, the influence of these factors and of rest interval and extension spacing was evidenced by the fluctuations of the proof stresses, the modulus at zero stress E_0 and its stress coefficients, C_0 and C'. Such fluctuations are not

*The second report (reference 2) was based on measurements obtained with an extensometer, which, though normally direct reading, was found later to contain a fixed calibration error; the extensometer assembly previously had been altered in an unorthodox manner. Knowledge of this error was obtained only after the report was first published. It is necessary, therefore, in order to secure proper quantitative data from this report to study an important errata sheet that should accompany all copies. The corrections indicated by this errata sheet are quite simple, involving only the multiplication of some modulus values by a fixed correction factor; this change does not affect qualitatively the results or conclusions given in the original report.

evident in figures 5 and 6. As previously stated, the gradual increase of internal stress with increasing extension (fig. 5) is evidenced by its depressing influence upon the shear proof stresses for the lower values of set. This effect has been noted also in tension measurements.

In tension tests of the annealed 18:8 alloy, it was noted that the linear and the quadratic stress coefficients differed considerably for different degrees of prior extension. In torsion tests, the linear stress coefficient C_0 is zero over nearly the whole extension range (fig. 6); whereas C', as evidenced by the slight curvature of the stress-modulus lines (fig. 4), is small. This difference in values obtained in tension and torsion tests is not wholly accounted for by differences in the two test procedures. It is probable that plastic extension influences the torsion coefficients to a somewhat lesser degree than it does the tension coefficients. In tension measurements, C_0 first increased, owing to the predominant influence of increasing internal stress, and later decreased, owing to the predominant influence of lattice expansion. The internal-stress factor evidently predominated only in the very early stages of extension in causing a rapid rise of C', which then decreased more gradually to zero within 12- to 16-percent extension.

The crystal-orientation factor, which exerts a predominating influence only after large extensions, is evidenced in tension tests in the later rise of the modulus curves of such materials as monel metal, Inconel (reference 2) nickel, and copper (reference 4) but not in the curves of 18:8 chromium-nickel steel (references 1, 2, and 4). The range of plastic extension in the present torsion tests, however, is insufficient to cause any appreciable crystal reorientation.

INFLUENCE OF PRIOR PLASTIC TORSION ON TORSIONAL ELASTIC PROPERTIES OF 18:8 CHROMIUM-NICKEL STEEL

Extension causes cylindrical deformation of the polycrystalline alloy if the tension is applied without transverse restraint. In the cold drawing or rolling of bars, additional transverse restraint is applied. Tensile loading can be shown to be equivalent to the simultaneous application of a volume-expansion force and shearing forces along planes situated at an angle of approximately $54^{\circ}44'$

with respect to the direction of loading. It was considered of interest, therefore, to study the influence of plastic shear alone upon the torsional elastic properties of the 18:8 alloy.

The test procedure was similar to that used in the previous investigation of the effect of prior extension upon the tensile elastic properties of metals (references 1 to 4). This procedure consists in obtaining correlated torsional stress-set and stress-deviation curves from test data for a single specimen, in the as-received condition and after imparting successive predetermined increments of plastic torsion. The method of determining individual torsional stress-set or stress-deviation curves is described in a preceding section. This procedure was followed for the annealed, the half-hard, and the hard 18:8 chromium-nickel steel.

In tension tests, the range of the plastic extension over which elastic properties were measured was limited to the range of uniform contraction of the specimens. In torsion tests, however, no significant change occurs in the cross section of the tube. The limitation to uniform deformation will be shear fracture, or buckling or helical deformation (reference 6) because of elastic or plastic instability.

The use of thick-walled tubing, as indicated in a preceding section, would decrease both the uniformity of stress distribution and the accuracy of determining the mean stress. These considerations led to a compromise in a value of 0.1 for the ratio of wall thickness to tube diameter. In the present investigation, observable helical deformation was found to be the only limitation to the range of uniform deformation.

Effect of Prior Plastic Torsion upon Torsional Elastic Strength of Annealed 18:8 Chromium-Nickel Steel

Shear stress-deviation and stress-set curves are shown in the upper and lower rows, respectively, of figure 7, as obtained after various increments of plastic torsion of a specimen of the as-received annealed alloy. The origin of each curve is shifted to the right a constant distance from the origin of the preceding curve. Each curve thus has its own scale of abscissas.

The curves from left to right were obtained consecutively after intervening (varying) amounts of prior plastic shear. Some of these shear increments were large; others were equivalent only to the plastic shear obtained in determining the previous shear stress-set curve. Between increments of torsion, the specimen was allows to rest before determining the subsequent stress-strain and stress-set curves. The duration of such a rest interval will have a pronounced influence upon the form of the stress-set and stress-deviation curves derived from subsequent measurements.

In making a series of torsion tests of a specimen, a total plastic shear of about 0.1 percent was usually obtained during the initial test. After a rest interval of about 30 minutes, a second series of load cycles was applied to the specimen and a somewhat greater total plastic shear was obtained. Occasionally, following a similar rest interval, a third series of measurements was made during which a large total plastic shear was obtained. The introduction of a third test in a series, a procedure that was not followed in the measurement of tensile elastic properties, was made in those cases where the time schedule permitted; it enabled the securing of additional useful test data within a given total time interval without influencing the results obtained from other tests in the series. Following this pair or trio of tests, the specimen was allowed to rest for a period of 18 hours or longer and the entire procedure was repeated. This schedule was continued until helical deformation of the test specimen occurred.

Certain changes will occur in the test specimen during a rest interval as evidenced by negative torsional creep during this period. Any variation in temperature with time after previous plastic shear, although effecting a change of dimensions of the specimen, will not cause any change in the torsion-meter readings. Since elastic shearing strain causes no change in volume, no subsequent thermal creep occurs (reference 1). Torsional negative creep probably is associated only with changes in lattice expansion following preceding plastic torsion.

The prior torsions are not indicated in figure 7. The curves are numbered consecutively, however, and the percentages of prior torsion, as calculated by equation 3 in terms of unit shear, may be found by referring to the corresponding points in figures 9 and 10. These points are calculated from curves in figure 7 in a manner previously described for figures 5 and 6.

The rest interval preceding each test is indicated by a designating symbol for the curves or points on the diagrams. In figure 9 the shear proof stresses are plotted against the corresponding percentage of prior plastic torsion. Differences in the increments of plastic torsion between curves permit the determination of the influence of this variable upon the form of the stress-set curve and the values of the derived proof stresses. The distribution of these increments over the range of total prior torsion is termed "torsion spacing." The shear stress-set relationship, as affected by plastic torsion, rest interval, and torsion spacing may be studied best by considering both the stress-set curves and the derived curves showing the variation of the shear proof stresses with different degrees of prior plastic torsion. The steeper the stress-set curve, the higher are the derived proof stresses. As indices of torsional elastic strength, the proof stresses based on 0.001- and 0.003-percent torsional proof set probably should receive more consideration than the proof stresses based on larger percentages of plastic shear. The 0.1-percent torsional proof set should be viewed as an index of the shear yield strength rather than as an index of the shear elastic strength.

The oscillations of the 0.001- and 0.003-percent proof-stress curve (fig. 9) generally are larger than, though similar to, the curves for the higher values of proof set. The oscillations are therefore principally due to changes in the properties of the test specimen and not to a lack of accuracy of the testing apparatus. These oscillations are qualitatively similar to those obtained in the tensile proof stress-extension curves for this alloy (references 1 and 2).

The stress-set curves (fig. 7) obtained after long rest intervals generally are less steep than those obtained after short rest intervals. For successive curves having short rest intervals of similar length, the curve corresponding to the smaller torsion spacing generally is steeper; this difference in steepness usually is not marked. These relationships are best illustrated in the derived diagram of figure 9. Points corresponding to long rest intervals are usually lower than those corresponding to short intervals. With two successive point corresponding to equal rest intervals, the second point, which corresponds to a large prior torsion spacing, usually is slightly lower.

The oscillations (fig. 9) due to the influence of rest interval and torsion spacing are superposed upon curves of variation of proof stresses due to prior plastic torsion alone. These last-mentioned curves, hereinafter termed "basic curves," are smooth in form but cannot be determined independently. The basic curves would be approximately parallel to curves drawn through the mean positions of the oscillations.

The basic 0.1- and 0.03-percent shear proof stress curves in figure 9 would rise continuously over the indicated range of prior torsion. The two lower basic curves, however, would show a rise over only the initial part of the range of plastic torsion and would thereafter descend gradually. These oscillations in the proof stresses (references 1, 2, and 4) probably are due to variations of internal stress. The decrease of proof stress following a long rest interval is attributed to negative creep induced by the preceding plastic deformation.

The rapid initial rise of the basic proof-stress curves (fig. 9) with prior torsion and the more gradual rise in the upper curves for subsequent stages of prior torsion (0.1- and 0.03-percent set) are attributed to work hardening of the metal in shear; that is, to the lattice-expansion factor.

The relative influence of plastic extension and plastic shear may be noted in a comparison of figures 5 and 9. The differences in proof-stress values for corresponding sets at zero abscissa are due to differences in the initial hardness of the specimens. As previously noted, this condition is due to the difference in treatment of the as-received-annealed and laboratory-annealed material, and may account for the generally lower value of proof stress for the curve in figure 5 than for the corresponding curve in figure 9.

Because two weeks had elapsed between the time of prior extension and the time of testing the specimens referred to in figure 5, it is presumed that the processes of negative creep were completed during this time interval. This conclusion is evidenced by the gradual rise of the proof-stress curves (fig. 5); if the process of negative creep was not completed in the extended specimens, there would have been a large increase in the proof-stress values between 0 and 0.5-percent extension (such as is indicated in fig. 9).

The general rate of increase of proof stress in the curves for 0.01- to 0.1-percent set for tensile extension (fig. 5) is greater than that for the corresponding curves for prior plastic shear (fig. 9). It is of interest, therefore, to obtain an index of initial work hardening of this metal in shear. If it is assumed that the ratio of shear strain to tensile strain is the same as the theoretical equivalence of these factors; that is, $1\frac{1}{2}:1$, the shear work-hardening index comparable to the previously defined tensile work-hardening index would be the ratio of the 0.1-percent shear proof stress at $4\frac{1}{2}$-percent prior torsion to that at 0 percent prior torsion. For the as-received annealed alloy TA (fig. 9), this ratio is 1.30, a value somewhat smaller than the value of 1.70 previously computed for the tensile work-hardening index (fig. 5). This difference in work-hardening index would be even greater, except for the rapid increase in shear proof stresses during the initial stages of prior plastic shear (fig. 9). The difference in value probably is largely due to the differences in hardness of the as-received annealed and laboratory annealed specimens.

For the higher values of prior plastic strain, the 0.1-percent torsional proof stress curve based on prior extension (fig. 5), is steeper than the curve based on prior torsion (fig. 9). At large values of prior deformation, however, the average rise of the 0.1-percent proof-stress curve in figure 5 over a prior-extension increment of 1.0 percent is approximately equivalent to the average rise of the corresponding curve in figure 9 over a prior-torsion increment of 1.5 percent. This relationship indicates that the work-hardening rates for large strain values of the alloy induced by tension or by torsion are approximately equivalent if the assumption regarding the equivalence of tensile to torsional strain is correct.

Effect of Plastic Torsion on Stress-Strain Relationship of Annealed 18 : 8 Chromium-Nickel Steel

The corrected stress-deviation curve of the annealed alloy (fig. 7) tends to decrease in slope and to increase in curvature with increase in plastic torsion. There is, moreover, no direct relationship between the form of this curve and the duration of the rest interval. The significance of variation in the form of the curve is revealed in the derived diagrams (figs. 8 and 10).

The stress-modulus lines in figure 8 show an increase in curvature with an increase in prior torsion. The initial slopes of these curves, however, do not vary in a regular manner. The variation with prior torsion of the shear modulus at zero stress G_0 and its linear stress coefficient C_0 is shown in the upper and lower curves, respectively, of figure 10. The shear modulus decreases with increasing plastic torsion at a gradually diminishing rate, reaches a minimum at about 8-percent torsion and then increases slightly with further torsion.

The value of C_0 fluctuates considerably throughout the range of torsion. A curve drawn through the mean position of the points, however, would rise rapidly at first, reach a maximum at a torsion of about $3\frac{1}{2}$ percent, and then recede only slightly thereafter. Slight differences in the form of the lower parts of the stress-modulus lines cause large variations in the value of C_0. Because of the marked curvature of the stress-modulus lines for this alloy, values of the quadratic stress coefficient C' have been derived from these curves and plotted against prior torsion (fig. 11). The derived curve may be considered as consisting of oscillations superposed upon a basic curve of smooth form. The basic curve would rise continuously with torsion, reach a maximum at a torsion value of about 12 percent, and decrease thereafter. This curve differs from the curve of variation with prior extension of the quadratic stress coefficient C' of the tensile modulus; as noted in references 2 and 4, the tensile curve rises abruptly to a maximum and then decreases at a lesser rate, reaching a zero value after 12- to 16-percent extension.

Values of the shear modulus at an intermediate stress of 20,000 pounds per square inch have been plotted against prior torsion in figure 10; these values were obtained directly from figure 8. This curve shows a general decrease of this intermediate modulus G_{20} throughout the indicated range of prior torsion; the curve is quite smooth in form. It is qualitatively similar to the intermediate tensile modulus E_{30} and E_{50} curves for this alloy.

It can be shown that the differences between values of G_{20} and G_0 at corresponding prior torsions are dependent principally upon the large values of the quadratic stress coefficient C', and only to a lesser extent upon the values of C_0. The differences between values of the tensile moduli E_0 and E_{50} at corresponding extensions (references 1 and 2) were found to be dependent principally upon the magnitude of the linear stress coefficient C_0. It must be noted that the G_{20} curve (fig. 10) is plotted over the lower range of deformation; whereas the E_{30} and E_{50} curves are plotted over somewhat higher ranges of deformation. The torsional stress-deviation curve for annealed 18 : 8 chromium-nickel steel, therefore, is nearly a cubic parabola throughout the range of prior torsion; whereas tensile stress-deviation curves of the form of cubic parabolas are obtained only in the initial range of prior extension. The oscillations of the curve for C_0 (fig. 10) and C' (fig. 11) are irregular and therefore bear no apparent relation to the magnitude of rest intervals and torsion spacings. It is probable that these irregularities are due partly to oscillations in internal stress and partly to limitations in the sensitivity of the apparatus. The relatively smooth forms of the curves of variation of G_0 and G_{20} with prior torsion (fig. 10) indicate that time intervals and torsion spacings exert little influence on the values of these indices.

Effect of Prior Plastic Torsion upon Torsional Elastic Strength of Half-Hard and Hard Steel

The torsional stress-set curves of the half-hard and the hard 18 : 8 chromium-nickel steels are shown in the lower portion of figures 12A and 12B, respectively. The amount of total prior plastic torsion corresponding to each curve may be obtained from the derived diagrams in figures 14 and 15.

The stress-set curves for both the half-hard and the hard alloy corresponding to long rest intervals generally are less steep than the curves immediately preceding or following which correspond to relatively short rest intervals. This phenomenon is revealed in the derived diagram of proof stress versus prior torsion (fig. 14) by the minima in proof stresses for indicated long prior rest intervals.

There is significant increase in proof stresses (fig. 14) accompanying the initial increment of prior torsion in every case. With further torsion, the proof-stress curves for 0.01- to 0.1-percent set rise. The proof-stress curves for 0.001- and 0.003-percent set for the half-hard 18 : 8 chromium-nickel steel (fig. 14A) first decrease and then increase with little oscillation; whereas the same curves for the hard alloy (fig. 14B) fluctuate appreciably, exhibiting a general decrease with prior torsion.

The oscillations in the curves probably are associated with variations in torsion spacing and rest intervals and are superposed upon basic curves showing more gradual variations. These basic curves would be approximately parallel to curves passing through the mean positions of the derived points. The minima in the curves at points corresponding to the longer prior rest intervals is attributed to negative creep. The variation of the basic curve for the most part probably is due to variations in the internal stress. The small rise in the upper proof-stress curves of figure 14 suggests that the influence of the lattice-expansion factor is slight.

Shear Modulus of Elasticity of Cold-Drawn Steel

The torsional stress-deviation curves for half-hard and hard cold-drawn 18 : 8 chromium-nickel steel are shown in the upper portion of figures 12A and 12B, respectively. The solid-line curves are derived from the broken-line curves by correcting for the torsion set obtained from the corresponding torsion stress-set curves immediately below. There is no apparent relationship between the form of the stress-deviation curves and the duration of the rest interval. All these lines, however, are prominently curved.

The stress-modulus lines in figure 13 were derived from the solid-line stress-deviation curves. With few exceptions, the stress-modulus lines are straight throughout their extent and slope with respect to the vertical. The linear stress coefficient C_0, the index of this slope, is indicated on each line. One notable exception to the indicated linearity is the initial stress-modulus line of the hard alloy. This line has practically zero slope over the lower part of the stress range but curves appreciably at higher stresses, indicating decreasing modulus values with increasing shear stress. No significant curvature occurs in the other stress-modulus lines.

Figure 15 shows the variation of the shear modulus of elasticity at zero stress G_0 and its linear stress coefficient C_0 with prior torsion for the half-hard and the hard 18:8 chromium-nickel steels. These values are derived from figures 12 and 13. The shear modulus at zero stress G_0 of the half-hard alloy is higher than that of the hard alloy. During the initial stage of prior torsion for the half-hard alloy (fig. 15A), G_0 decreases rapidly to a minimum but varies little with further torsion. For the hard alloy (fig. 15B), the value of G_0 fluctuates with change in prior torsion; a mean curve of this variation would show gradually decreasing values of shear modulus with increasing torsion.

The linear stress coefficient of the modulus C_0 for both half-hard and hard 18:8 chromium-nickel steel fluctuates somewhat but generally increases with increase in prior torsion; these osciallations are greatest for the hard alloy. The oscillations in the curve of C_0 in general have a like course to the curve of G_0 (fig. 15).

Influence of Various Factors upon Torsional and Tensile Elastic Properties as Affected by Plastic Deformation

The influence of various factors upon torsional and tensile elastic properties as affected in each case by plastic extension was discussed in the preceding section. In the present discussion, the variation of the tensile elastic properties with progressive plastic extension is compared with the variation of the torsional elastic properties with progressive plastic torsion.

The increase in internal stress with increasing plastic deformation of the annealed alloy tends to lower both torsional (fig. 9) and tensile proof stresses (references 1 and 2) for the smaller set values (0.003- and 0.001-percent set). Furthermore, this increase in internal stress tends to increase the linear (C_0) and the quadratic (C') stress coefficients of the modulus for both torsion and tension. This increase also tends to cause a slight initial rise in the G_0 and E_0 curves (fig. 10 and reference 2).

The general decrease of the shear modulus at zero stress G_0 of the annealed alloy with progressive prior torsion (fig. 10) probably is due to the dominant influence of the lattice-expansion factor; this factor also was apparently dominant in the lowering of the tensile modulus at zero stress E_0 with progressive prior extension. The lattice-expansion factor predominates in causing a decrease of the quadratic stress coefficient of the shear modulus C' for the higher degree of torsion (fig. 11); it became dominant; however, at somewhat smaller equivalent deformations in causing lowering of C' in the tensile tests. This same factor is effective in causing a rise of the proof stresses for the higher values of set with progressive prior deformation in both torsional (fig. 9) and tensile tests. The general decrease in shear proof stresses after a long rest interval following prior torsion is probable evidence of a partial decrease in hardness of the metal, which is a manifestation of the influence of the lattice-expansion factor.

As previously noted, plastic deformation tends to change the orientation of grains of annealed polycrystalline metals from the random to a preferred state. Because of directional variation of the modulus of elasticity of a metal crystal, this change to a preferred orientation may affect the mean modulus of elasticity of such aggregates. The effect of this change, however, usually becomes evident only after severe plastic deformations.

This factor is prevalent in causing at indicated large deformations the rise of the curves showing variation of the tensile modulus E_0 with progressive extension for monel metal, Inconel, copper, and nickel. It is not prevalent, however, in the tensile curves for annealed 18 : 8 chromium-nickel steel. Although the range of deformation indicated in the G_0 curve (fig. 10) is small, the general decrease in slope of this curve may possibly be associated with a change in crystal orientation.

In reference 1, the influence of prior plastic extensions upon the tensile elastic properties of the half-hard and hard 18 : 8 chromium-nickel steel was shown. The half-hard grade used for that investigation had received approximately the same amount of cold work as had the half-hard material used in the present investigation; the hard materials used for the two investigations differed considerably. The comparison will therefore be made only of the results of the torsion and tension tests upon half-hard 18 : 8 chromium-nickel steel. The two steels used in the present investigation differed little in hardness.

An initial rapid rise of all the proof-stress-deformation curves of the cold-drawn alloy occurs in all cases whether tested in tension or torsion. This rise probably is due to the reduction of internal stress accompanying initial deformation. The smaller rate of rise of the proof-stress curves for 0.03- and 0.1-percent set with further deformation is also characteristic of both the tensile and torsional cases. Although this condition may be due partly to the further relief of internal stress, it probably is due to a greater extent to the additional work hardening of the metal; that is, to the lattice-expansion factor. In tensile tests of the half-hard alloy and in torsional tests of the hard alloy, the proof-stress curves based on lower set values fluctuate during the further stages of deformation. The more abrupt oscillations probably are due to fluctuations in rest interval. The proof-stress values corresponding to the longer prior rest intervals generally are lower.

The torsional- and tensile-modulus (G_0 and E_0) curves of the cold-drawn alloy (see fig. 15 and reference 1) exhibit a decrease with increase in deformation. This condition probably is due to the dominating influence of the lattice-expansion factor. The initial value for G_0 for the hard 18 : 8 chromium-nickel steel is low in the torsion case (fig. 15), but is high in the tensile case (reference 1); this suggests that the tubing used in torsion tests may have been given a stress-relief annealing treatment following cold drawing during manufacture.

INFLUENCE OF ANNEALING TEMPERATURE ON TORSIONAL ELASTIC PROPERTIES OF 18 : 8 CHROMIUM-NICKEL STEEL

The effect of annealing temperature upon the tensile elastic properties of 18 : 8 chromium-nickel steel was discussed in references 2 and 3. It was found that by annealing the cold-worked 18 : 8 alloy within a range of temperature below that of recrystallization, a definite increase in tensile proof stresses and tensile modulus of elasticity was obtained. Similar experiments have been made to ascertain the effect of annealing temperature on the torsional elastic properties in the present investigation. A series of torsion-test specimens of the hard-alloy tubing was annealed at temperatures ranging from room temperature to 1900° F with each specimen annealed at a different temperature. A stress-set curve and a stress-deviation curve for each specimen are shown in the lower and upper portions, respectively, of figure 16. The temperature at which each specimen was annealed is indicated on the corresponding curve. The curves for an annealing temperature of 1900° F occupy only a small stress range; they are based on the same data as are the initial curves in figure 3 which were drawn to a more open stress scale. They are reproduced in figure 16 for the purpose of comparison.

Effect on Torsional Elastic Strength

For specimens annealed within the range of 300° to 1100° F, the initial part of the shear stress-set curves is more nearly vertical than that for the cold-drawn tubing as received (fig. 16). The maximum shear stress reached over the indicated torsion-set range is greatest for annealing temperatures ranging from 500° to 900° F.

The variations in form of the stress-set curves are more clearly revealed in the derived curves (fig. 18) showing variation of proof stresses with annealing temperature. The shear proof stresses increase with increasing annealing temperature up to about 900° F and then decrease rapidly with further increases in temperature.

Effect on Shear Modulus of Elasticity

and Its Stress Coefficients

The solid-line stress-deviation curves in the upper row of figure 16 have been corrected for permanent shear. These corrected curves tend to become more nearly vertical with increase in the annealing temperature. A high value of the shear modulus for the fully annealed metal (1900° F) is indicated by the slope to the left of the corresponding corrected curve. Such a negative slope is caused by the selection of an assumed shear-modulus value smaller than the modulus of the test material. The stress-deviation curves for temperatures of 300°, 500°, 700°, 900°, and 1300° F are somewhat curved, indicating a variation of the modulus with shear stress.

The derived stress-modulus lines for metals annealed at various temperatures are given in figure 17. Curves indicated by annealing temperatures of 300°, 500°, 700°, 900°, and 1300° F have positive values of C_O; the remaining lines have an initial zero slope. The stress-modulus lines are curved at the higher values of stress. The quadratic stress coefficients of the modulus corresponding to these lines, however, are small; no tabulation of these values is given.

Figure 19 shows the variation of the shear modulus of elasticity at zero stress G_0 and its linear stress coefficient C_0 with annealing temperature; G_0 shows a general increase with increase in annealing temperature with the value of the modulus being nearly constant over the range from 500° to 1100° F. A further increase in annealing temperature, which produces softening causes a more rapid rise in the modulus. The linear stress coefficient of the modulus C_0 reaches a maximum for an anealing temperature of 500° F but decreases at higher temperatures.

Influence of Various Factors upon Torsional and Tensile Elastic Properties

The curves showing the variation of torsional and tensile proof stresses with different annealing temperatures are similar in form. A maximum is reached in both sets of curves at about 900° F (fig. 18 and references 2 and 4). With increase of annealing temperature up to 900° F, there is evidence of a significant decrease in the internal stress. This change of internal stress tends to increase the shear (fig. 18) and tensile proof stresses. With further increase in temperature, the influence of recrystallization or softening of the metal will predominate in causing a lowering of both torsional and tensile proof stresses.

The curves showing variation of the modulus of elasticity and of its linear stress coefficient with different annealing temperatures for both torsion and tension are similar in form. The influence of recrystallization; that is, elimination of work-hardening or lattice-expansion effects, evidently predominates over the whole range of annealing temperature and causes a rise with progressively increasing temperature of both the shear and tensile moduli of elasticity. The decrease of internal stress in the intermediate temperature range (500° to 1100° F) probably is responsible for the decreased slope of the modulus-temperature curve in this region (fig. 19).

Maxima in the curves of C_0 with annealing temperature are obtained at an intermediate temperature in both torsion and tension. The cause for these maxima has not been ascertained.

CONCLUSIONS

The effects of plastic deformation (extension or torsion) on the shear elastic properties of 18 : 8 chromium-nickel steel were studied and in many respects were found qualitatively similar to the effects of plastic extension on the tensile elastic properties of this metal. In the following general conclusions, the exceptions will be noted.

1. An incomplete view of the torsional elastic properties of this alloy is obtained by considering either the stress-set or stress-strain relationship alone. Consideration should be given both relationships.

2. Shear stress-set curves may be used to derive proof stresses that represent the stresses causing various amounts of permanent set. Corresponding shear stress-strain and stress-set curves may be used to derive corrected stress-strain curves representing the variation of elastic strain with stress.

3. Curves showing variation of shear proof stresses with prior plastic deformation often consist of oscillations superposed on a gradual wavelike mean curve. These oscillations generally are associated with variations in the duration of the rest interval and the degree of deformation spacing.

4. The proof stresses representing the permanent set values of 0.01, 0.03, and 0.1 percent generally increase continuously with prior plastic deformation. The 0.001-percent proof stresses and, in some cases, the 0.003-percent proof stresses do not increase or decrease continuously but fluctuate and shown little general upward or downward trend with deformation. These oscillations are generally more pronounced for the work-hardened than for the annealed alloy.

5. The variation of the shear proof stress with prior plastic deformation is affected by: (a) macroscopic internal stress, which is caused by nonuniformity of plastic deformation of different parts of the effective cross section; (b) microstructural internal stress, which is caused by initial differences in the resistance to plastic deformation of variously oriented grains of a polycrystalline aggregate and to differences in strength of different

microconstituents; and (c) space-lattice changes involved in work hardening; that is, the work-hardening factor or the lattice-expansion factor.

6. The variation of the shear proof stresses with prior plastic deformation is affected by the rate of work hardening and by the change of internal stress, both macroscopic and microstructural. Work hardening tends to increase the proof stress. Increase of internal stress tends to decrease the proof stresses; especially the proof stresses that may be regarded as indices of elastic strength (0.001- and 0.003-percent proof stress). The lack of a significant rise of these lower proof stresses with prior plastic deformation probably is due to a general increase of internal stress.

7. Rest, following deformation, tends to lower the proof stresses, especially those representing the lower values of set (0.001 and 0.003 percent). It is believed that rest probably causes some decrease in hardness of the metal.

8. Curves of variation of the secant modulus with stress may be derived from corrected shear stress-strain curves. The stress-modulus lines for the annealed alloy frequently are curved. With progressive prior plastic torsion the curvature of the shear stress-modulus line increases slowly, reaches a maximum after moderate plastic torsion, and then decreases. With prior plastic extension, however, the curvature of the tensile stress-modulus line increases rapidly and then decreases; this line becomes straight after moderate extension of the alloy. The stress-modulus lines for the work-hardened alloy in both shear and tension exhibit negligible curvature.

9. Linearity of the shear stress-modulus line indicates that the corresponding stress-strain line is a quadratic parabola. The curvature of such a parabola; that is, the slope of the stress-modulus line, may be measured by the linear stress coefficient of the modulus. The shear modulus at zero stress may be obtained by extrapolating the stress-modulus line to zero stress.

10. When the shear stress-modulus line is curved from the origin, a second constant, the quadratic stress coefficient of the shear modulus, is required to represent more adequately the curvature of the stress-modulus line. For some metals free from the effects of cold

work, the linear stress coefficient is zero, the quadratic stress coefficient has a positive value, and the stress-strain line is a cubic parabola. When the stress-modulus line is curved and not vertical at the origin, the stress-strain line may be viewed either as a superposition of a cubic parabola on a quadratic parabola or as a parabola with an exponent between 2 and 3.

11. When the shear modulus at zero stress, its linear and quadratic stress coefficients, and the shear proof stresses have been derived, a fairly complete description of the elastic properties of a metal in shear is available.

12. Because of the great directional variation of the modulus of elasticity of some metal crystals, a change in orientation of the grains of a polycrystalline aggregate may greatly affect the modulus-deformation curve. Annealing may have a significant influence on the crystal orientation and thus affect the modulus of elasticity.

13. The curves of the shear modulus at zero stress with prior plastic deformation for many metals are continuously influenced by three important variables: crystal orientation, internal stress, and lattice expansion. The curves of variation of the linear and quadratic stress coefficients of the modulus with plastic deformation are continuously influenced by the last two factors. A change in dominance from one factor to another is accompanied by a reversal of the corresponding curve. The effect of the reorientation factor on the 18 : 8 chromium-nickel alloy is not known, but it is not sufficient to become dominant in any of the curves obtained for this alloy.

14. For the annealed alloy, the internal stress factor is dominant in causing the slight initial rise in the curve of variation of the shear modulus at zero stress with the first stages of deformation, beyond which the lattice-expansion factor becomes continuously dominant in causing a decrease of the modulus.

15. Dominance of the internal-stress factor causes a rise in both the linear and quadratic stress coefficients of the modulus during the initial stages of deformation of the annealed alloy. Upon further deformation, the lattice-expansion factor becomes dominant and causes a lowering of these indices. The range of prior deformation within which the quadratic coefficient rises, however, is somewhat greater in shear than it is in tension. The internal-stress factor is dominant over a greater range of deformation in shear than in tension.

16. An increase of internal stress tends to cause an increase of the linear stress coefficient of the modulus. A decrease of internal stress accompanying plastic extension or annealing tends to cause a decrease of this coefficient.

17. Annealing the cold-drawn alloy at about 900° F for relief of internal stress causes a significant increase in shear proof stresses, especially those for 0.003- and 0.001-percent set.

18. The shear modulus at zero stress for the cold-drawn alloy shows a general increase with increase of annealing temperature at least up to 1900° F. This increase is due to the decrease of work-hardening or lattice-expansion effects. The shear modulus at zero stress, however, is almost constant for annealing temperatures over the range 500° to 1100° F. In this range the effect of decreasing lattice expansion with increasing annealing temperature is balanced by the effect of decreasing internal stress.

An investigation of the influence of plastic deformation and of annealing on the torsional elastic properties of a number of nonferrous metals is in progress. It will be of interest to learn to what extent the conclusions drawn relative to the influence of plastic deformation on the tensile and torsional elastic properties of the 18 : 8 alloy may apply to these other metals.

National Bureau of Standards,
Washington, D. C., November 9, 1942.

NOTE: The "measure" given on the illustrations is to be used for scaling the curves in order to get close readings as desired.

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TABLE I.– CHEMICAL COMPOSITION OF 18 : 8 CHROMIUM–NICKEL STEEL

Grade of hardness as received	Designation	Carbon (percent)	Chromium (percent)	Nickel (percent)
Annealed	TA	0.06	18.5	10.4
Half–hard	TB	.06	18.5	10.4
Hard	TC	.07	18.5	10.4

TABLE II.– DETAILS OF THERMAL AND MECHANICAL TREATMENTS OF 18 : 8 CHROMIUM–NICKEL STEEL

Grade of hardness, as received	Specimen designation*	Annealing temperature (deg F)	Time held (hr)	Cooled in	Mechanical treatment following heat treatment
Annealed	TA	----------	As received		
Half–hard	TB	----------	As received		
Hard	TC	----------	As received		
	TC–3	300	1	Air	
	TC–5	500	1	Air	
	TC–7	700	1	Air	
	TC–9	900	1	Air	
	TC–11	1100	1	Air	
	TC–13	1300	1	Water	
	TC–19	1900	1	Water	
	TC–19R–0.5	1900	1	Water	Extended 0.5 percent
	TC–19R–1	1900	1	Water	Extended 1.0 percent
	TC–19R–2	1900	1	Water	Extended 2.0 percent
	TC–19R–3	1900	1	Water	Extended 3.0 percent
	TC–19R–5	1900	1	Water	Extended 5.0 percent
	TC–19R–10	1900	1	Water	Extended 10.0 percent
	TC–19R–20	1900	1	Water	Extended 20.0 percent

*In the specimen designation the number following the initial dash indicates the annealing temperature in hundreds. The letter R following this number indicates that the specimen has been reduced further by extension; the amount of extension in percent is designated by the number following the second dash.

TABLE III.- TORSIONAL PROPERTIES FOR 18 : 8 CHROMIUM-NICKEL STEEL

Grade of hardness as received	Specimen designation	Initial shear proof stress (lb/sq in.)					Elastic coefficients	
		0.1-percent proof set	0.03-percent proof set	0.01-percent proof set	0.003 percent proof set	0.001-percent proof set	Initial shear modulus at zero stress, C_o (lb/sq in.)	Initial linear stress coefficient of the shear modulus, C_o
Annealed	TA	23,000	19,700	16,300	14,700	10,000	11.42×10^6	0
Half-hard	TB	53,500	47,900	37,000	29,000	21,000	11.06×10^6	13.9×10^{-7}
Hard	TC	66,900	55,000	43,200	30,200	11,000	10.54×10^6	0
	TC-3	69,100	58,000	49,300	39,600	29,000	10.83	3.9×10^{-7}
	TC-5	72,200	62,100	53,200	44,500	29,000	10.97	4.4
	TC-7	73,000	63,000	55,000	46,900	40,500	10.98	3.6
	TC-9	73,300	63,800	56,200	48,100	37,500	11.03	3.6
	TC-11	68,200	59,700	52,600	44,500	28,000	11.0	0
	TC-13	54,300	46,100	33,200	20,000	10,500	11.07	3.4
	TC-19	13,700	10,600	7,700	5,400	4,400	11.30	0
	TC-19R-0.5	16,600	14,200	10,500	4,500	2,600	11.11	0
	TC-19R-1.0	18,200	16,000	11,900	7,200	4,200	11.07	0
	TC-19R-2.0	21,000	17,000	12,600	8,000	5,000	11.24	0
	TC-19R-3.0	23,300	18,800	13,700	7,500	4,300	11.01	0
	TC-19R-5.0	25,900	20,800	14,700	9,500	7,000	10.97	4.0
	TC-19R-10.0	32,500	24,800	16,600	10,000	7,200	10.80	0
	TC-19R-20.0	42,000	28,400	18,400	11,700	9,100	10.53	0

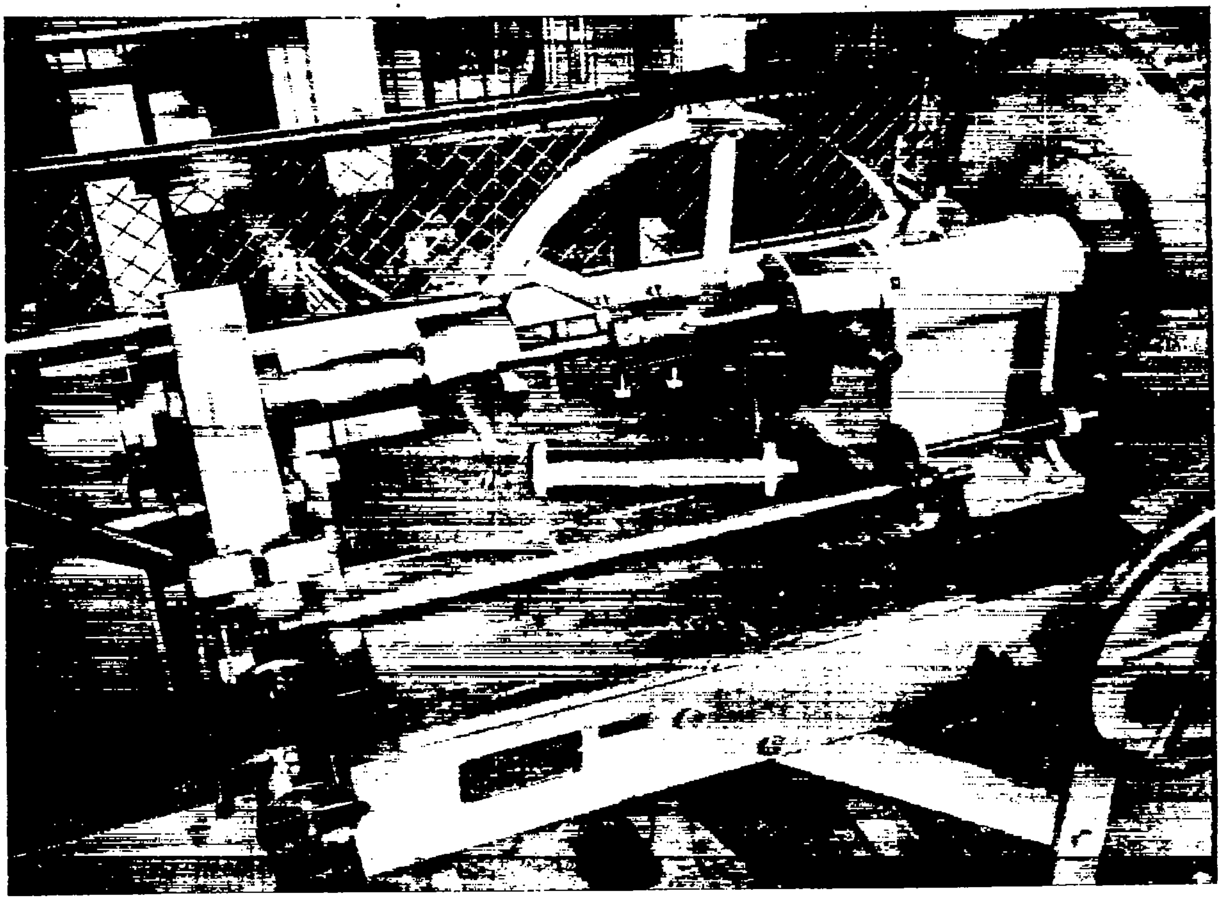


Figure 1.- Torsion-testing machine with specimen and torsion meter mounted.

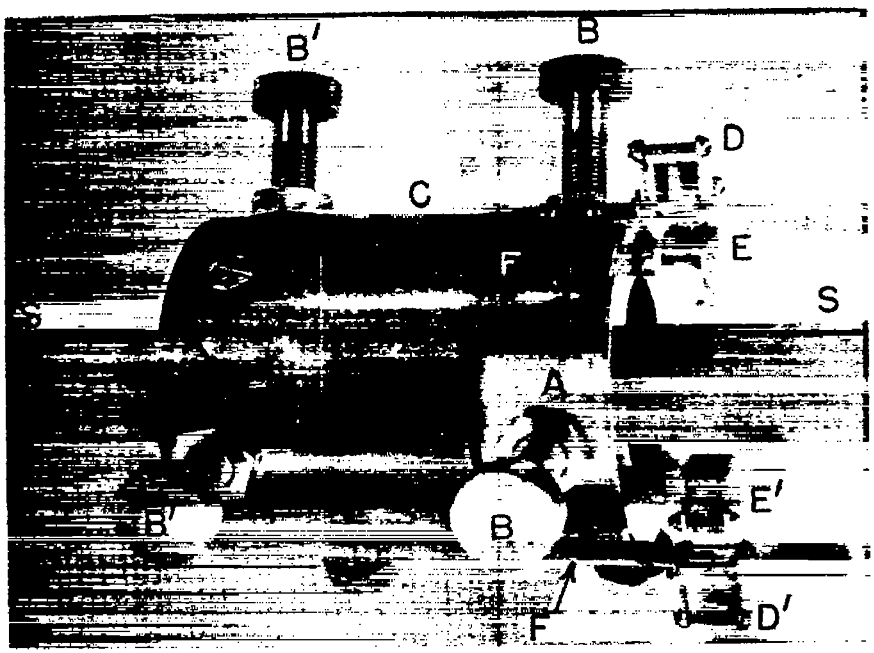


Figure 2.- Optical torsion meter.

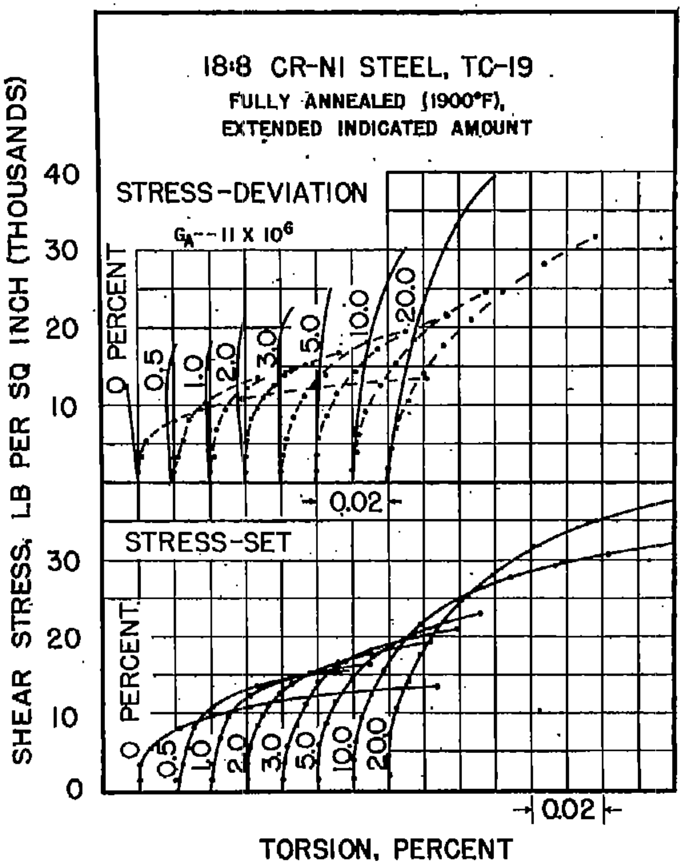


Figure 3.- Shear stress-deviation and stress-set curves for fully annealed 18:8 chromium-nickel steel TC-19 as influenced by prior extension.

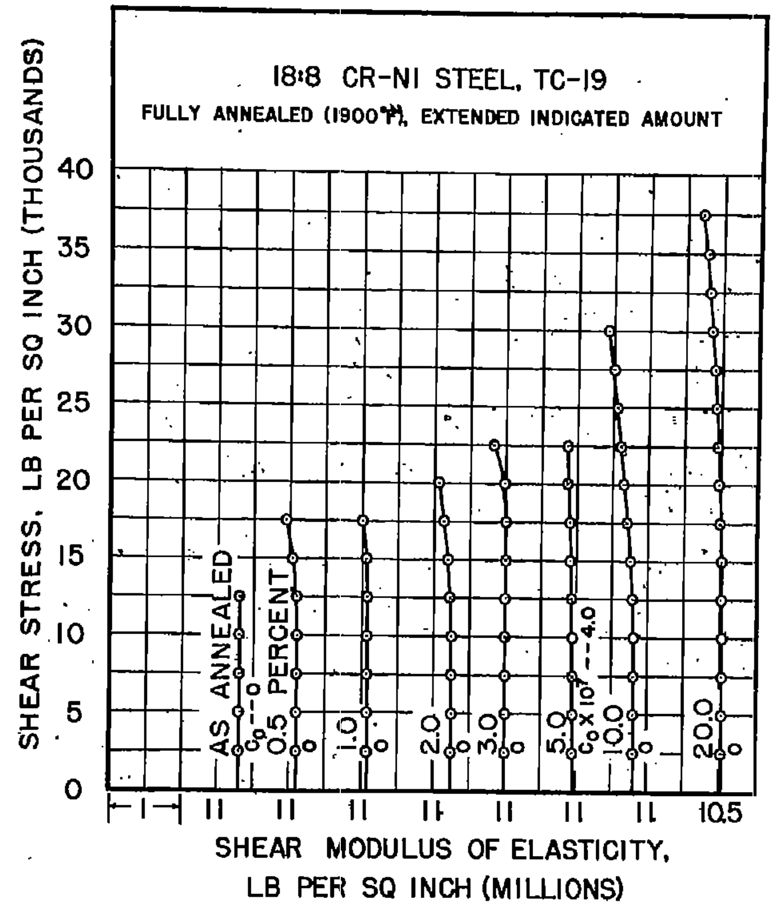


Figure 4.- Shear stress-modulus lines for fully annealed 18:8 chromium-nickel steel TC-19 as influenced by prior extension.

(Measure with 1/50".)

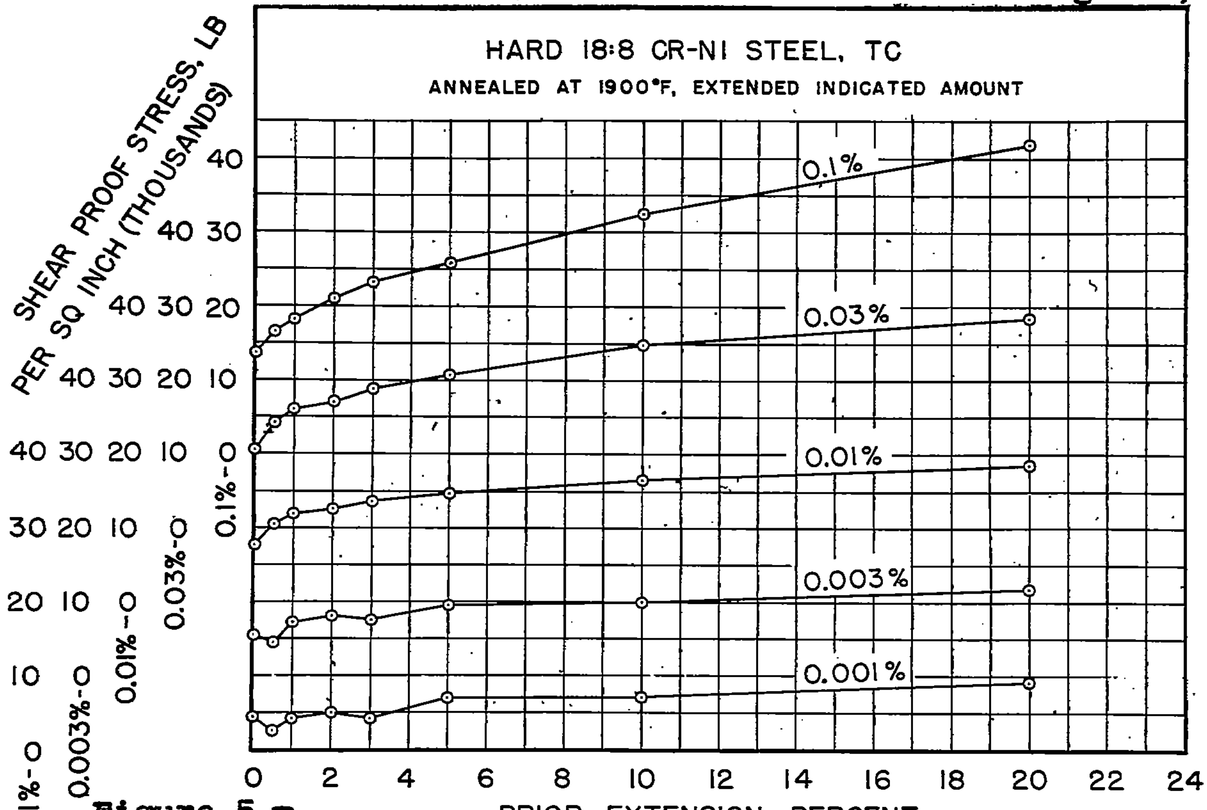


Figure 5.- Variation of shear proof stresses with prior extension for fully annealed 18:8 chromium-nickel steel TC-19.

(Measure with 1/50")

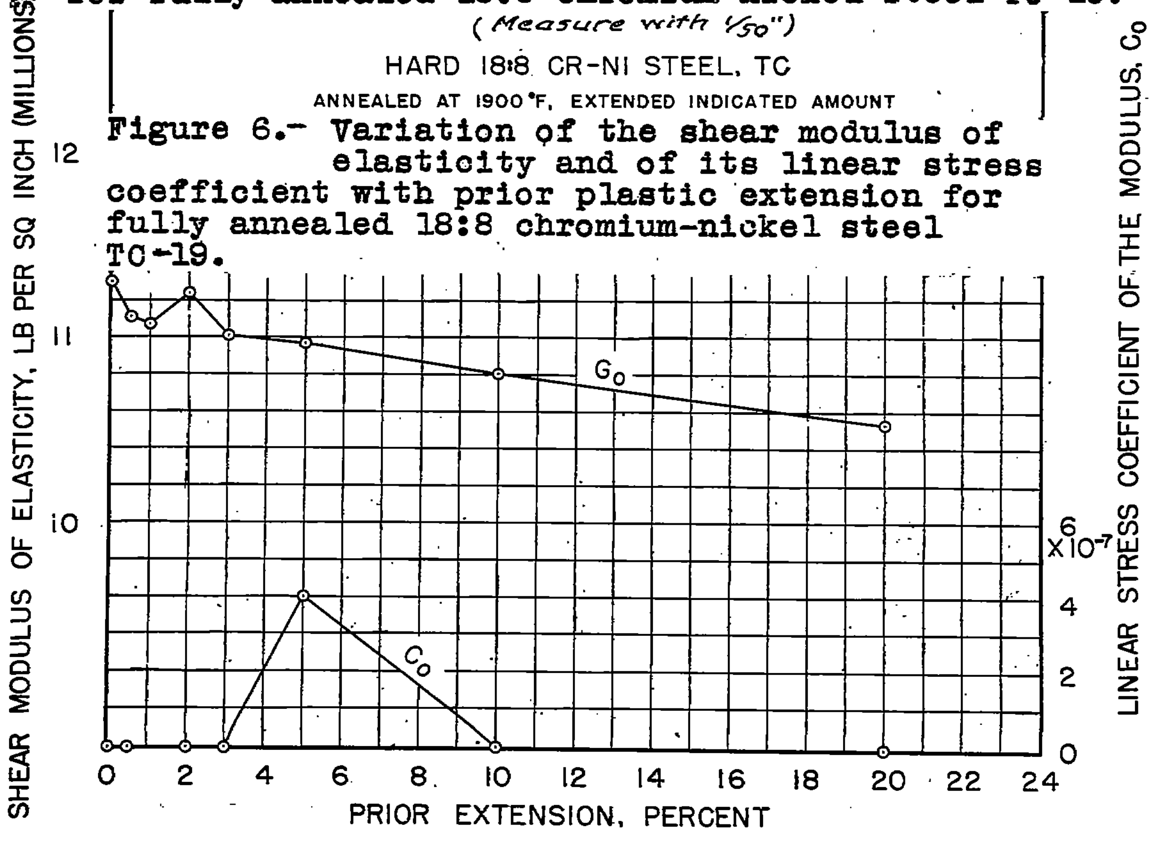


Figure 6.- Variation of the shear modulus of elasticity and of its linear stress coefficient with prior plastic extension for fully annealed 18:8 chromium-nickel steel TC-19.

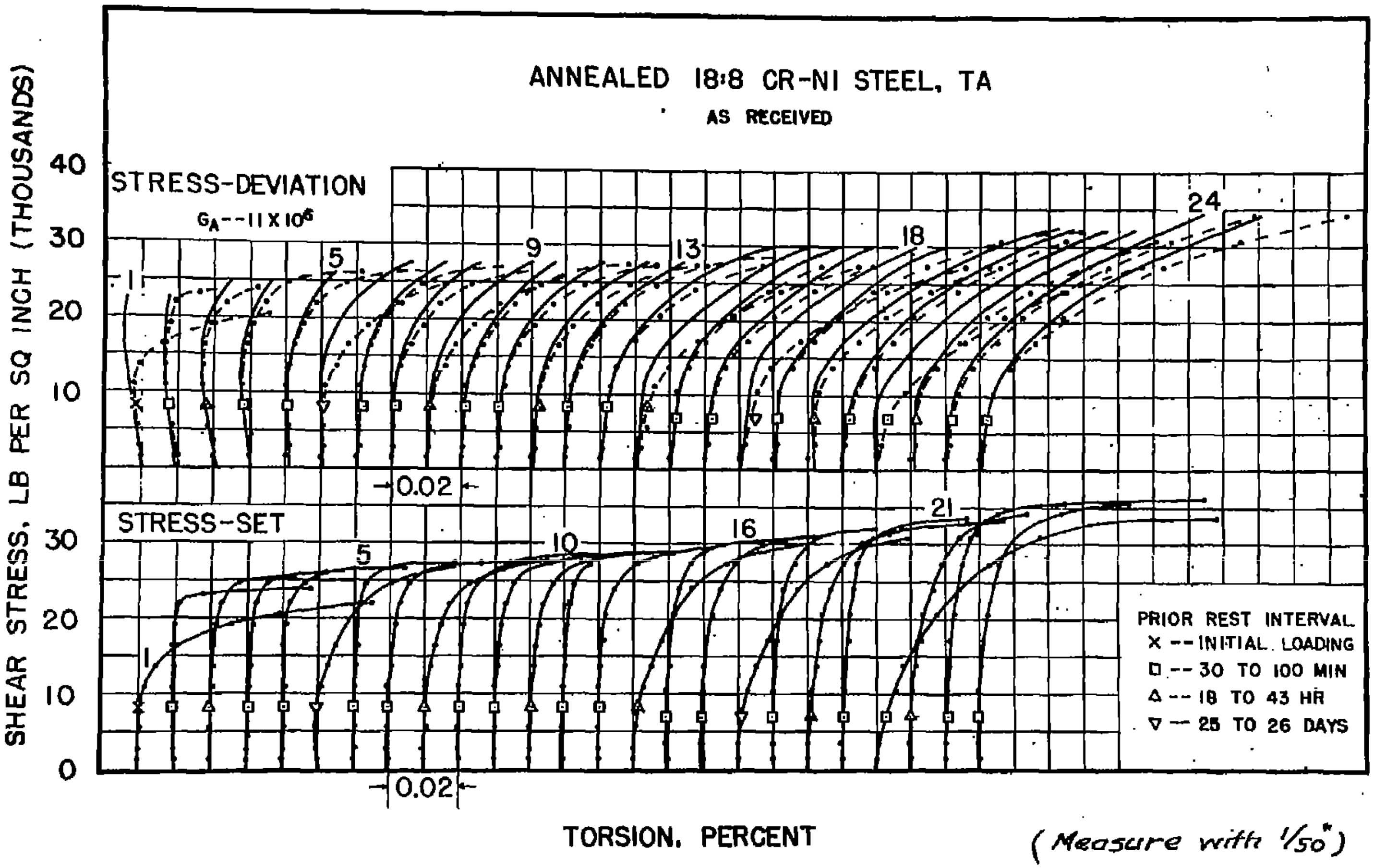


Figure 7.- Shear stress-deviation and stress-set curves for annealed 18:8 chromium-nickel steel TA as influenced by prior torsion.

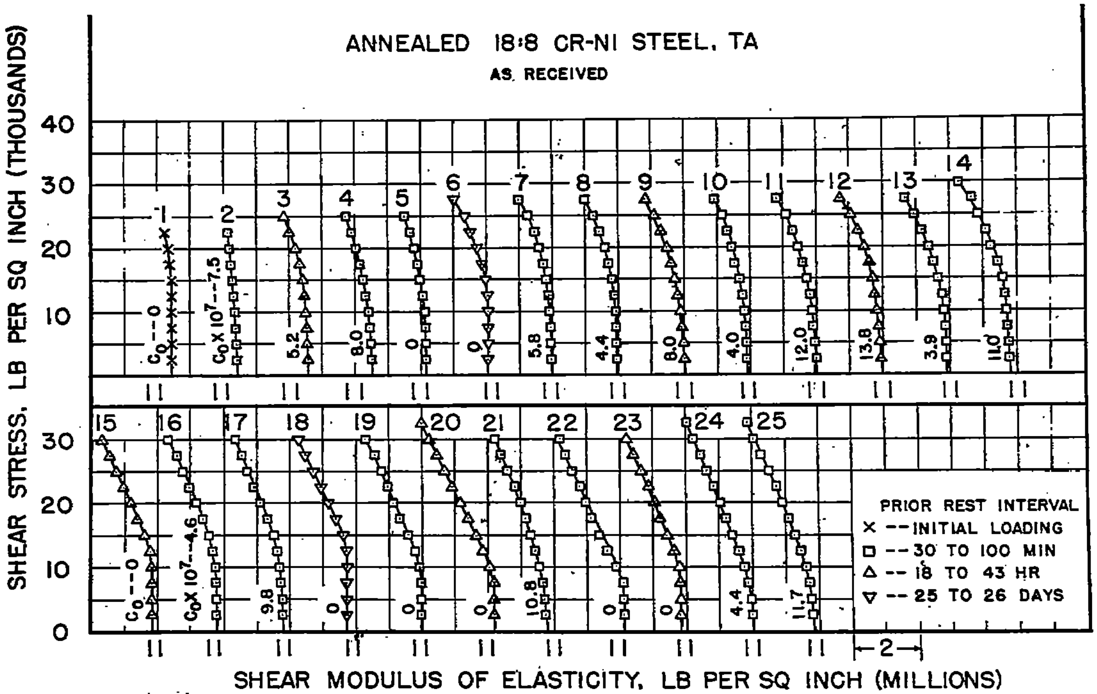
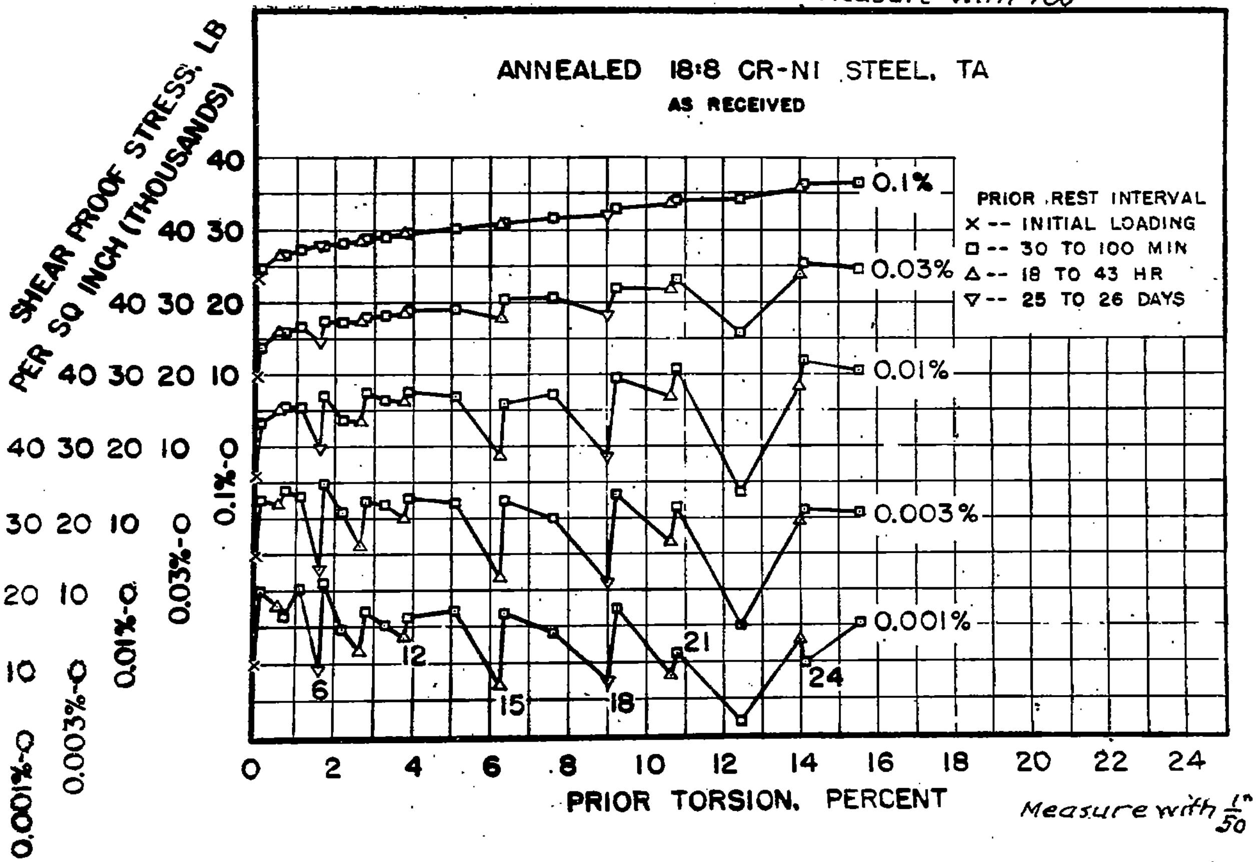


Figure 8.- Shear stress-modulus lines for annealed 18:8 chromium-nickel steel TA as influenced by prior torsion.

Measure with 1/60"



Measure with 1"/50

Figure 9.- Variation of shear proof stresses with prior torsion for annealed 18:8 chromium-nickel steel TA.

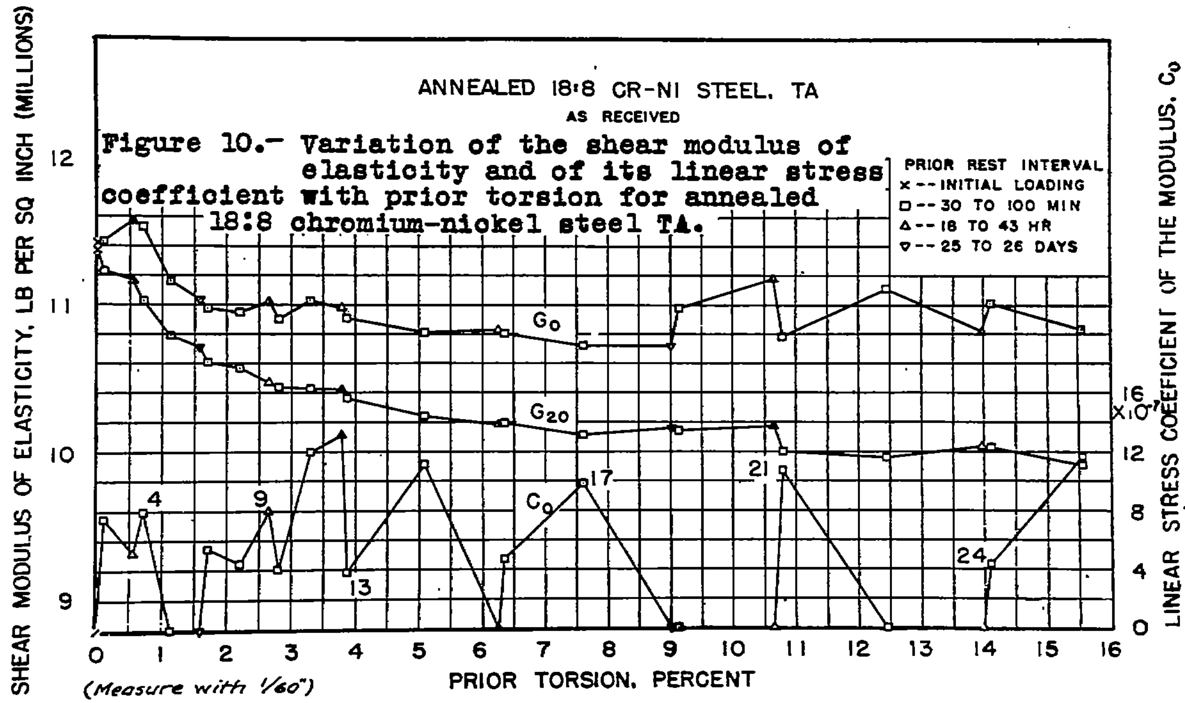


Figure 10.- Variation of the shear modulus of elasticity and of its linear stress coefficient with prior torsion for annealed 18:8 chromium-nickel steel TA.

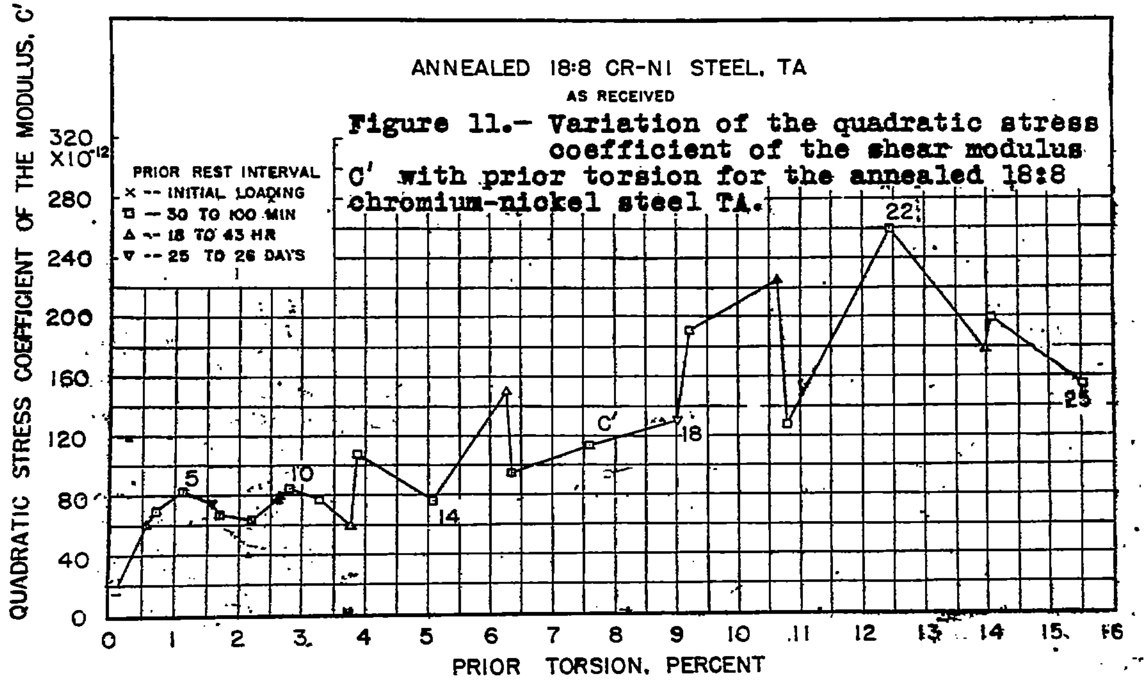


Figure 11.- Variation of the quadratic stress coefficient of the shear modulus C' with prior torsion for the annealed 18:8 chromium-nickel steel TA.

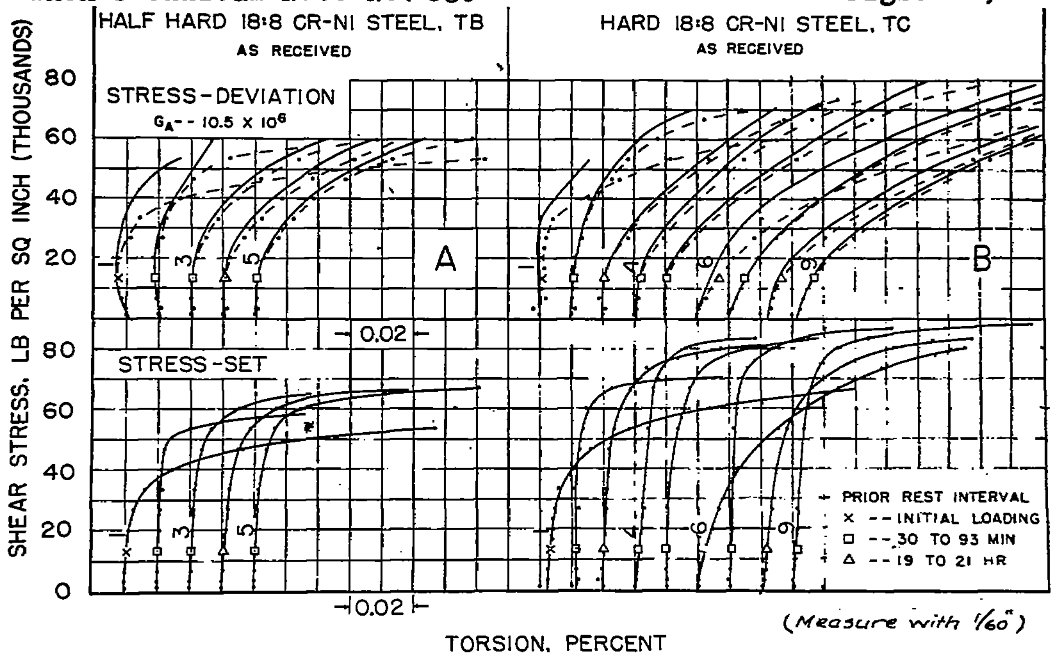


Figure 12.- Shear stress-deviation and stress-set curves for cold-drawn 18:8 chromium-nickel steel as influenced by prior torsion.

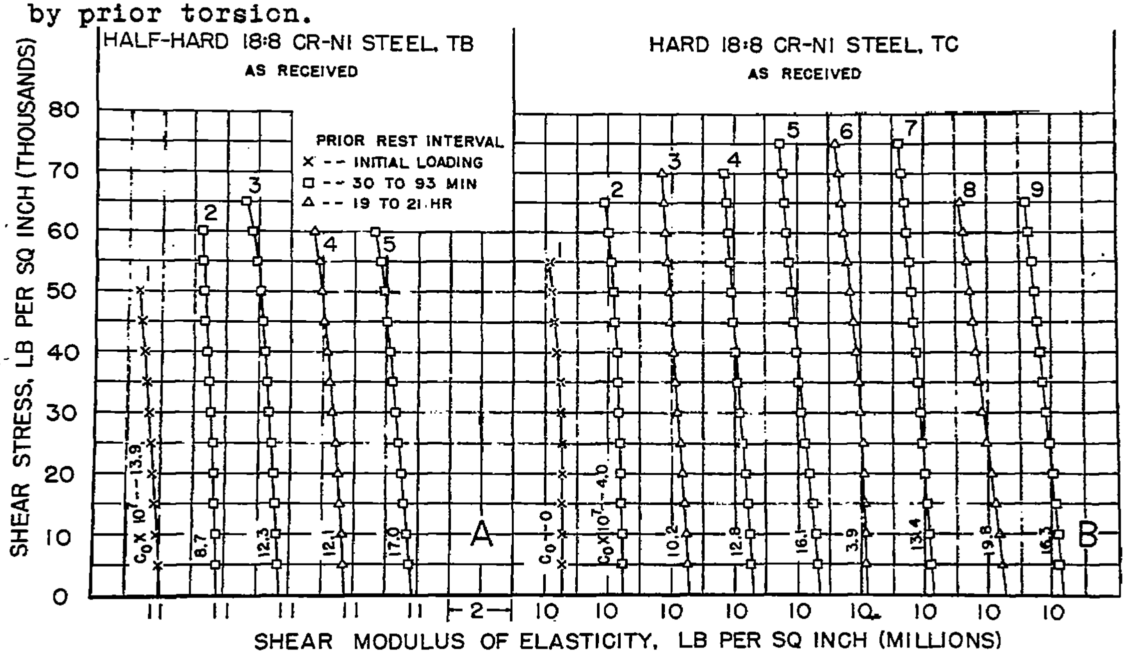


Figure 13.- Shear stress-modulus lines for cold-drawn 18:8 chromium-nickel steel as influenced by prior torsion.

(Measure with 1/50")

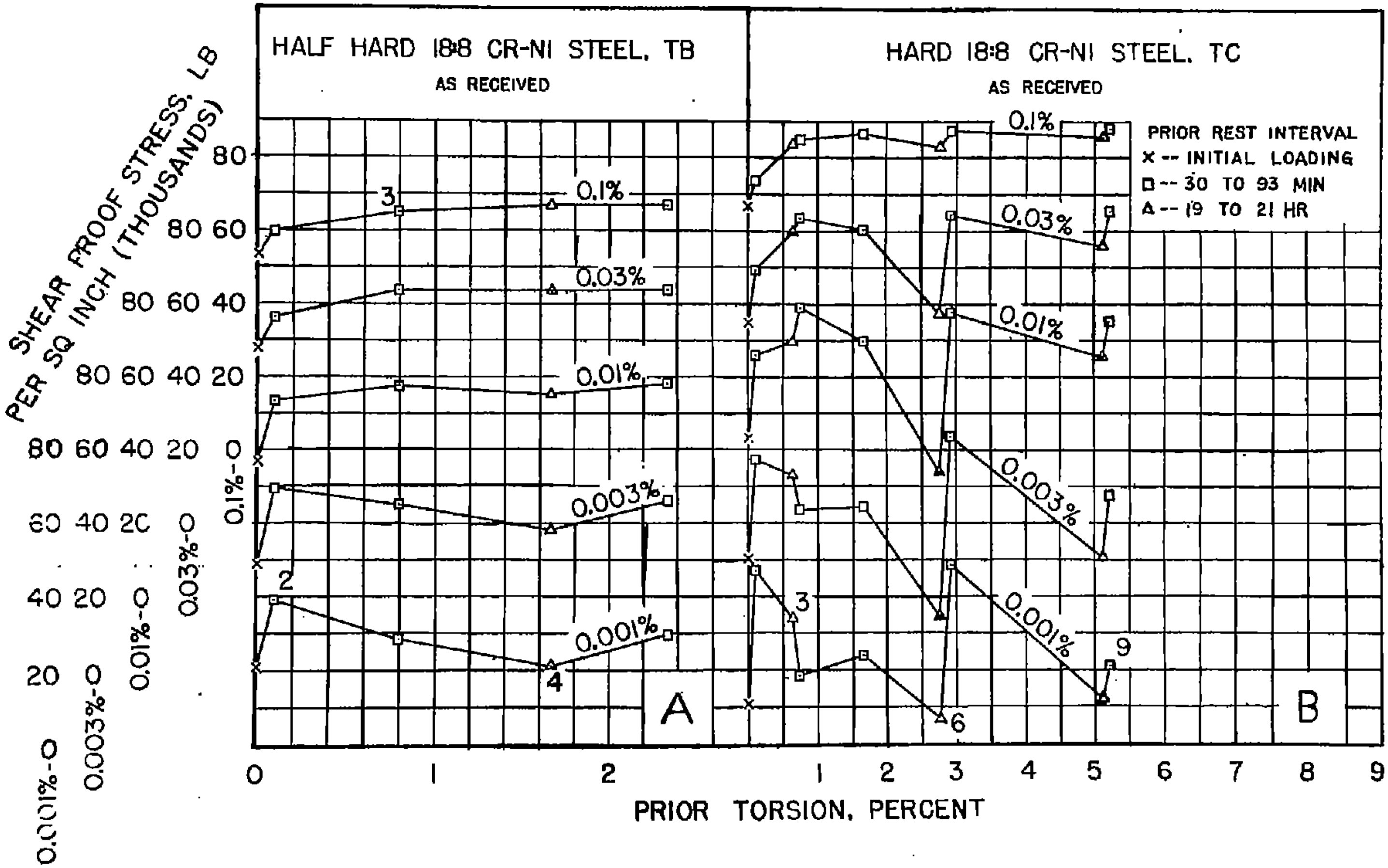


Figure 14.- Variation of shear proof stresses with prior torsion for cold-drawn 18:8 chromium-nickel steel.

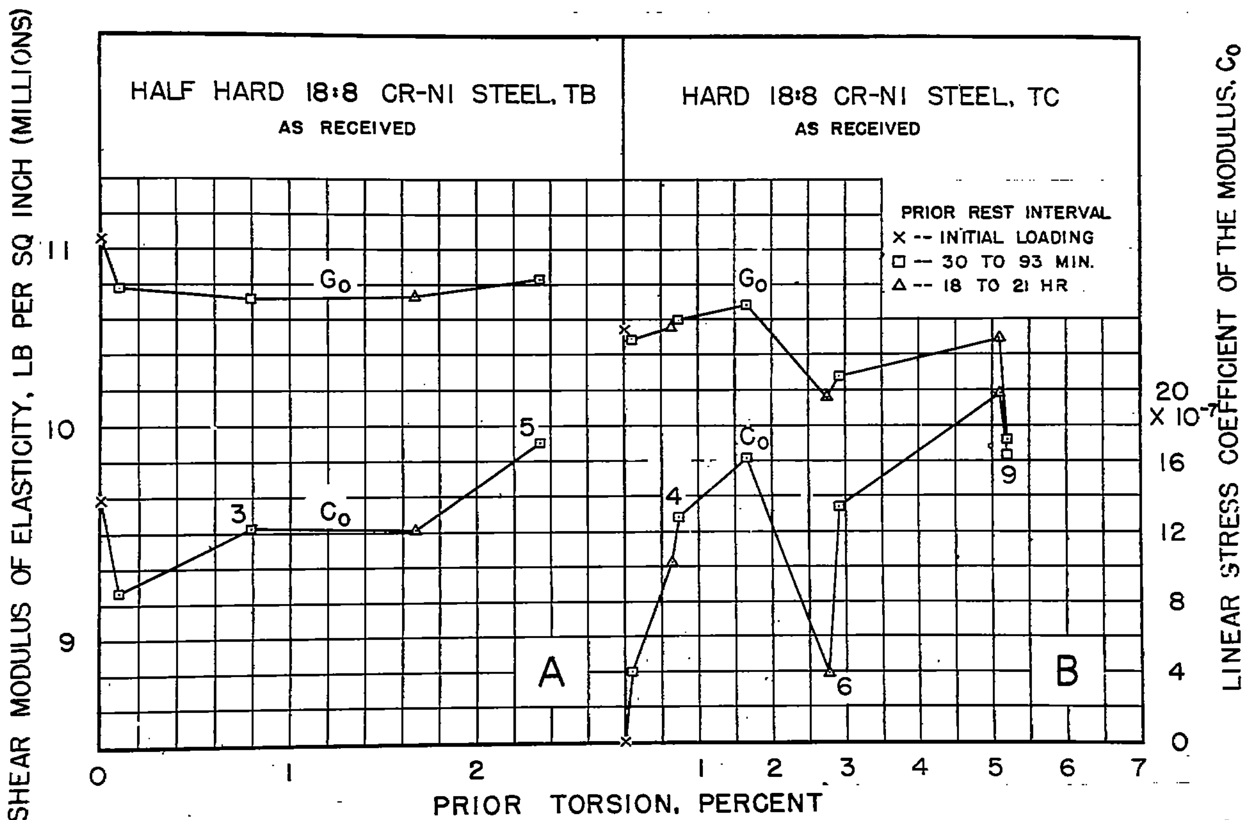


Figure 15. Variation of the shear modulus of elasticity and of its linear stress coefficient with prior torsion for cold-drawn 18:8 chromium-nickel steel.

(Measure with 1/50")

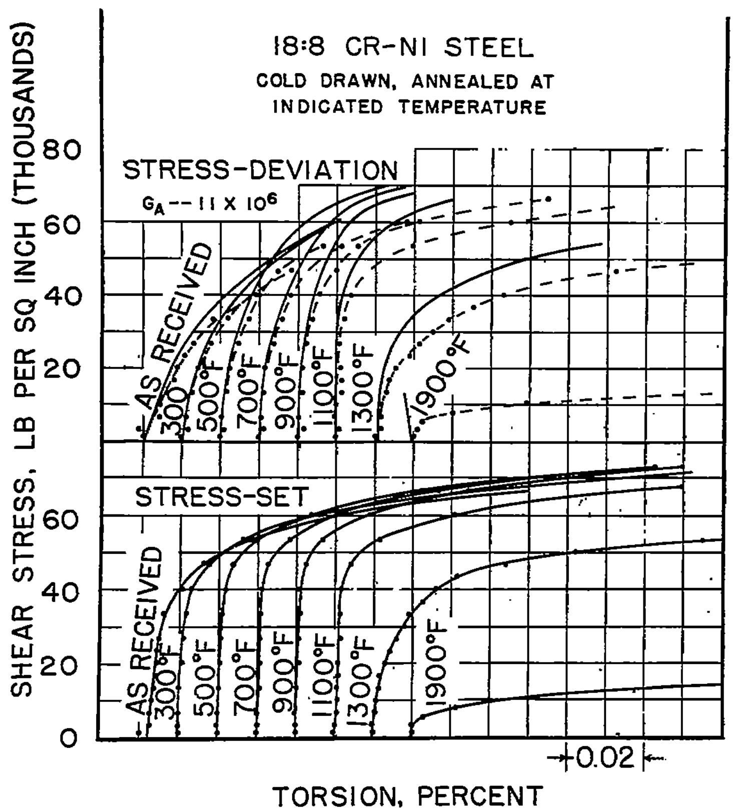


Figure 16.- Shear stress-deviation and stress-set curves for cold-drawn 18:8 chromium-nickel steel TC as influenced by annealing temperature.

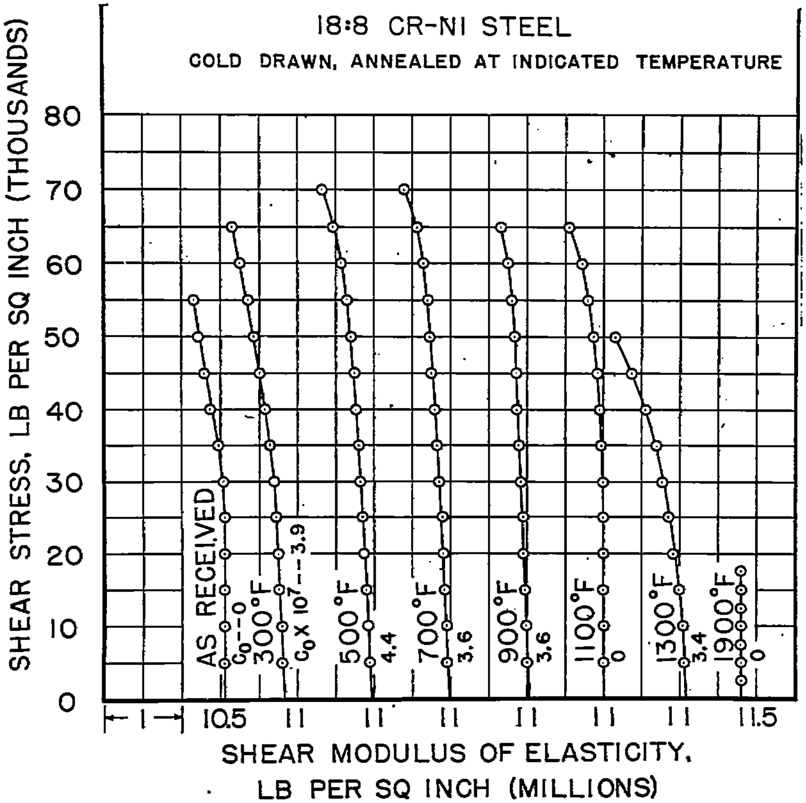
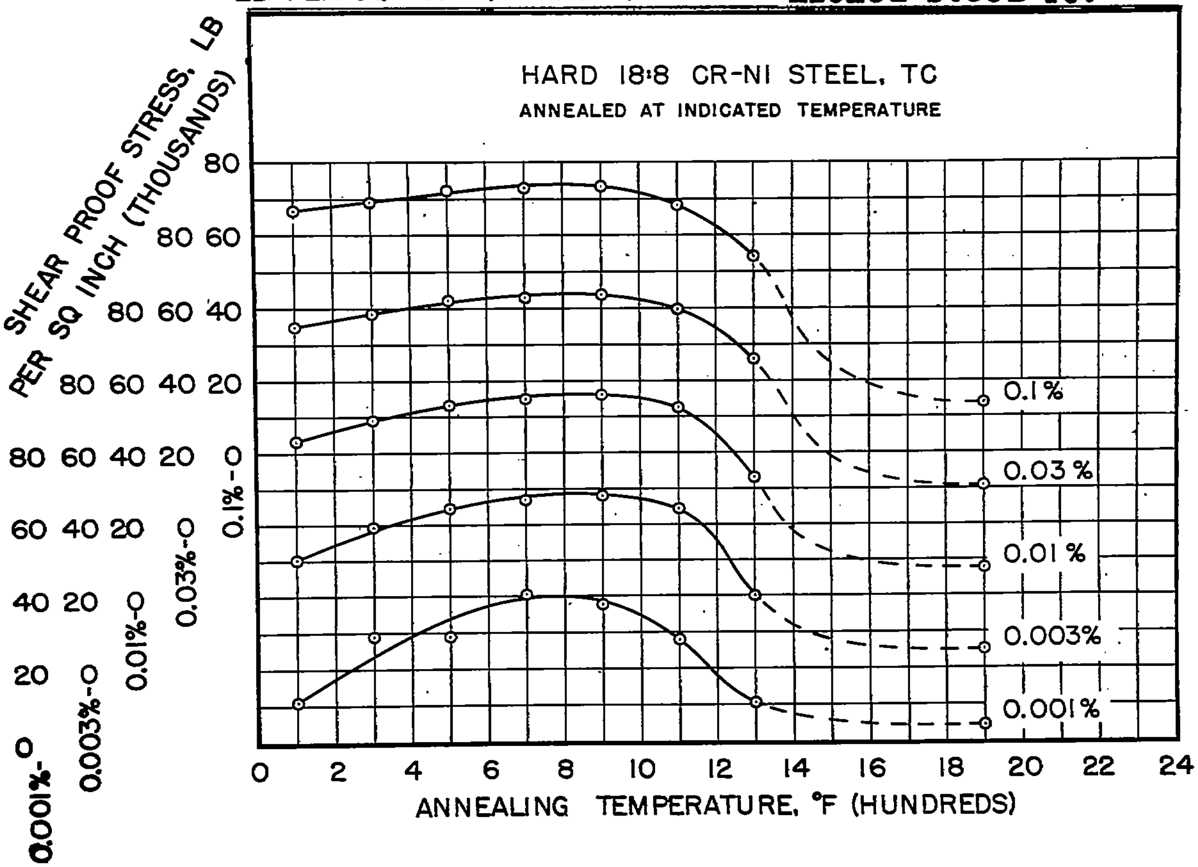


Figure 17.- Shear stress-modulus lines for cold-drawn 18:8 chromium-nickel steel TC as influenced by annealing temperature.

(Measure with 1/50")

Figure 18.- Variation of shear proof stresses with annealing temperature for 18:8 chromium-nickel steel TC.



(Measure with 1/50")

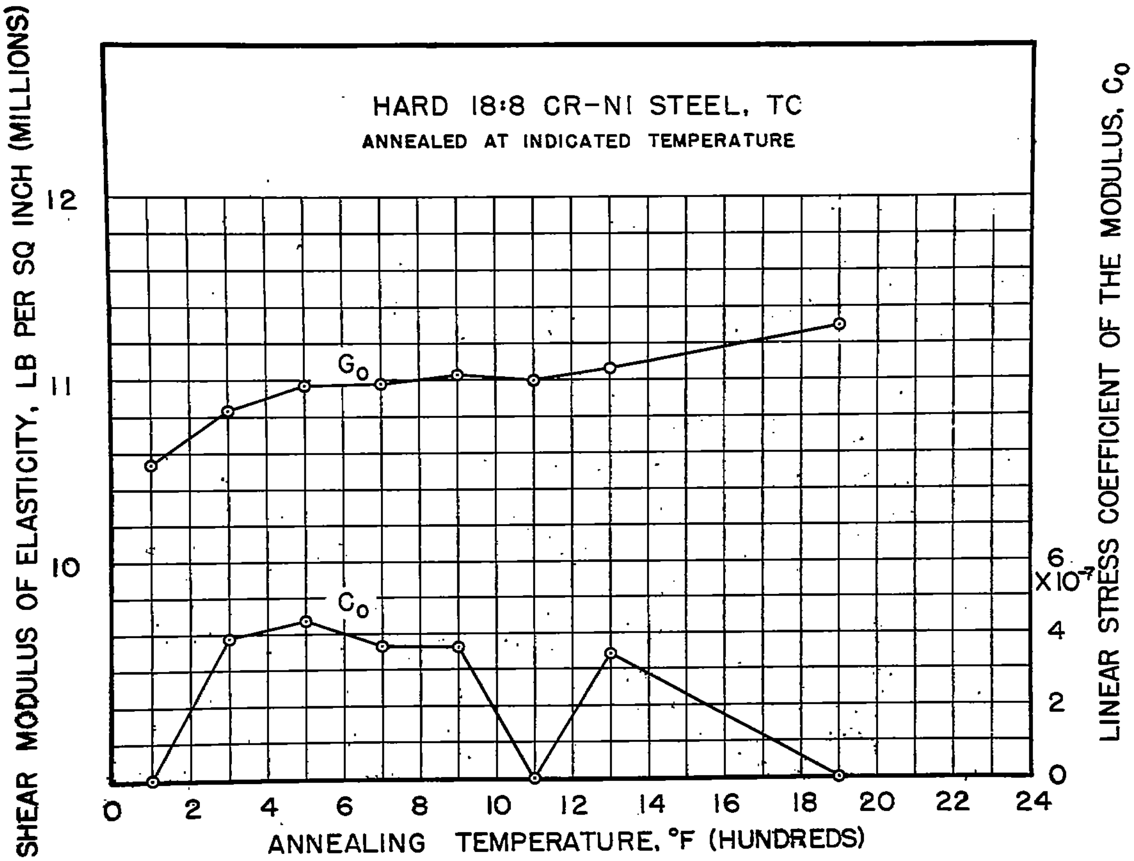


Figure 19.- Variation of the shear modulus of elasticity and of its linear stress coefficient with annealing temperature for 18:8 chromium-nickel steel TC.